G.E.C. Journal

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THE FLOODLIGHTING OF BUCKINGHAM PALACE.

A night view of Buckingham Palace floodlighted by 188 G.E.C. projectors, each equipped with a 1000-watt Osram lamp, the total aggregate beam candle power exceeding 62,000,000. This untouched photograph is published by courtesy of His Majesty's Master of The Household. The installation was carried out by Messrs. Troughton & Young Ltd., London.

G.E.C. Journal

VOL. II. NOVEMBER, 1931. No. 3.

Precision in Incandescent Lamp Manufacture.

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IT is not possible in the space available here to deal completely with the physical and chemical controls which are necessary in order that uniformity of performance in incandescent lamps shall be maintained with certainty, and since we are concerned here more particularly with those aspects of the problem which affect the illuminating engineer, it is proposed to concentrate on those factors which affect the light output and lamp efficiency and on those others which determine the uniformity of the light centre length.

TUNGSTEN POWDER.

When the tungsten lamp was first introduced the filaments were squirted from a paste of finely divided metallic powder, following the old carbon filament practice, but for the last twenty years tungsten has been drawn into wire. A somewhat coarser metal powder is prepared from precipitated tungsten oxide and pressed into bars which are subsequently consolidated by electrical heating into a crystalline metallic form and then hammered into rods and drawn through diamond dies. The invention of the gas-filled lamp in 1912 introduced a new requirement, namely that helical coils of tungsten wire should remain stable even when heated to temperatures exceeding 2,300°C. This problem has continuously engaged the attention of engineers and scientists in the lamp factories throughout the world and, although it is probable that finality has not yet been reached, the modern practice is very much the same in all those factories making filaments for high class incandescent lamps.

The tungsten oxide is precipitated from an alkaline solution containing tungsten, many precautions being taken to obtain this oxide as pure as possible, and, in particular, free from certain especially undesirable impurities, among which may be named compounds of titanium, iron, etc. This precipitated tungsten oxide is reduced by heating in hydrogen, leaving the metal in the form of powder. It is now generally accepted that the physical and chemical states of this powder largely determine

whether or not the wire made from it will come up to the standards demanded in modern coiled filament lamps.

Leaving aside the question of chemical purity, it is still not certain whether the oxide precipitation or the reduction process is the more important in determining the suitability of the material, but it is the practice to determine the grain size distribution of the metal powder, and metals which do not conform to some definite specification are not utilized in the production of filaments.

A highly magnified photograph of a tungsten metal powder is shown in fig. 1. Distribution

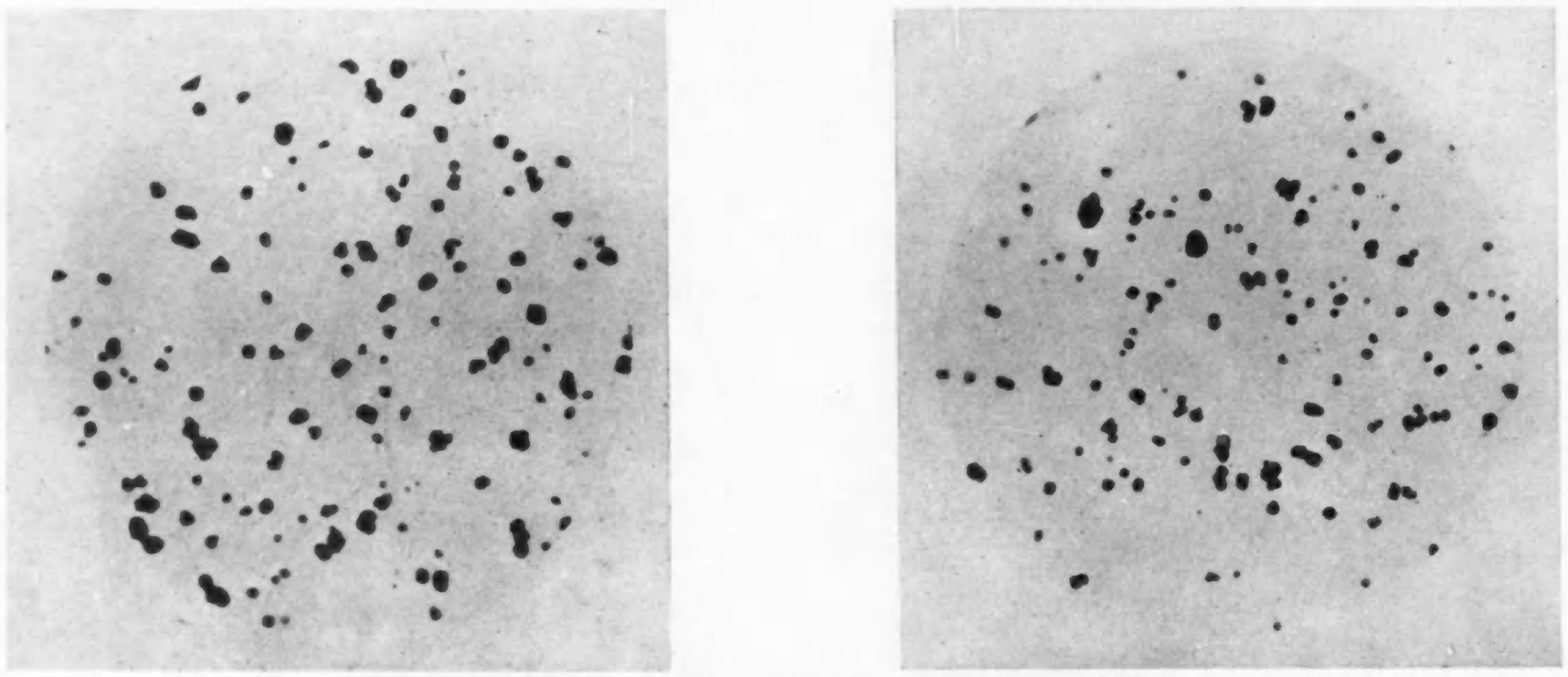


Fig. 1.—Tungsten metal powder, magnification × 500.

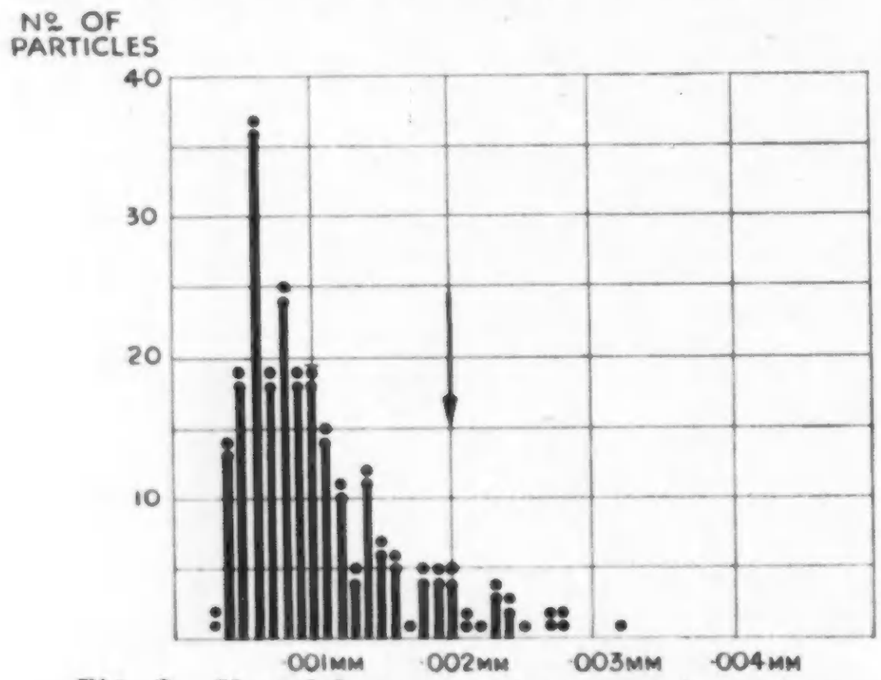


Fig. 2.—Unsatisfactory tungsten metal powder; size distribution.

curves of particle size are plotted by actual measurement of particles in samples, spread out in turpentine on a microscopic slide, photographed and subsequently projected on to a screen.

As an illustration of the precision necessary to maintain the standard, figs. 2 and 3 show graphically the powder size distribution in tungsten powders which are respectively unsatisfactory and satisfactory for filament making.

The scale of dimensions should be particularly noted; it will be seen that the bulk of the particles in the satisfactory metal lie between a range of size of 1μ to 2μ (1μ equals 0.001 mm. which is equal to 0.0004 inch), whereas in the metal deemed unsatisfactory there is a much higher proportion of finer particles. It is of interest to note that one half of the weight of the metal lies on either side of the arrow head.

WIRE DIMENSIONS.

As already stated, the metal powder is pressed into ingots which are heat treated in hydrogen, first to about 1,200°C. in a tubular electric resistance furnace to give sufficient strength for handling, and

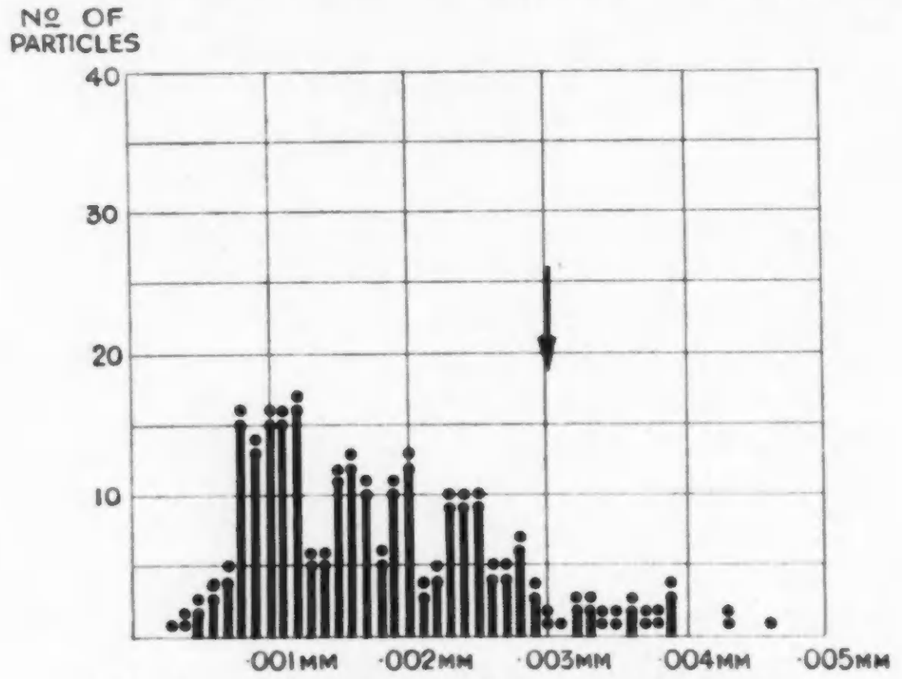


Fig. 3.—Satisfactory tungsten metal powder; size distribution.

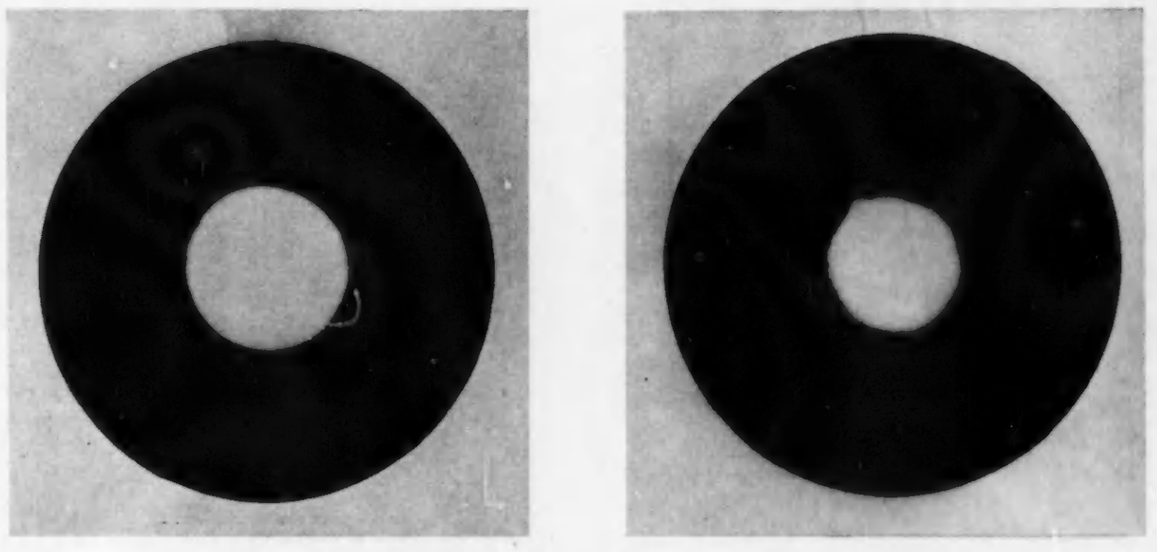
then by self heating with a current to a temperature of approximately 2,800°C. These ingots are subsequently hammered and drawn through dies. The wires most commonly used in lamps for general lighting service vary in diameter from 0.015 mm. to 0.05 mm., *i.e.*, from 0.0006 inch to 0.002 inch.

In order that the average life of batches of lamps shall be greater than 1,000 hours at the efficiencies now specified, these wires must be very accurately

round and must not have local variations in diameter as large as 0.5 per cent to 1 per cent; therefore the allowable local variations in a wire of diameter 0.001 inch are less than one-hundred thousandth of an inch. The measurement of such variations presents a difficult problem in metrology, which at first sight appears to be suited only to a standardizing National Laboratory; various devices however have been designed to perform this operation on an industrial scale, and there is one in use which not only measures the variations but automatically records them over lengths of wire running to several thousands of metres.

nominal weight of any wire is of the order of ± 1.5 per cent, which, if one includes the possible balance errors, means a variation in the finest wires (that used for High Voltage 15 watt lamps) amounting possibly to ± 3.5 per cent (or nearly ± 2 per cent. in diameter). The balances are checked several times daily with standard platinum check weights of 1, 2 and 5 mg. High absolute accuracy in these weights is not essential but it is usual to have them calibrated at a standardizing laboratory in case replacement becomes necessary.

The figure of ± 3.5 per cent, given for the maximum error tolerated in the weight per unit



Good die × 500 Bad die

Good die × 200 Bad die

Fig. 4.—Comparison of good and bad dies.

Fig. 4 shows enlarged views of two wire-drawing dies of about 0.001 inch diameter, one satisfactory and the other unsatisfactory because of slight faults having developed on its circumference; these photographs give some idea of the degree of accuracy it is necessary to maintain in the dies.

Not only have wires to be uniform throughout their length but it is also necessary to reproduce wires of the same diameter regularly, over long periods of time. Die size, and therefore filament size, is usually controlled by weighing fixed lengths of wire cut in special gauges, the weighing being done on a torsion balance capable of a reproducible accuracy of 0.01 mg. The tolerance allowed on the length of the finest wire, corresponds to variations in diameter of only ± 0.00001 inch ($\pm 1'' \times 10^{-5}$) from wire to wire.

Before leaving this matter of filament size it should be added that wires falling towards the extreme sizes allowed by the tolerances described are subjected to another correction. In order that the average product should approach more nearly to a definite objective in rating than would be the case if all the wires falling within these tolerances were used under identical conditions, it is usual to make a compensation in filament design (see next section) which partially corrects the error introduced when a wire is slightly above or below the theoretically correct size.

MANDRIL DIMENSIONS.

The principle of the gasfilled lamp demands that the filament wire shall be wound in the form of a fine helix. Uniformity of production and reduction of diversity of type among the machines utilized in lamp production has tended towards the adoption of such "coiled" filaments in vacuum lamps also, so that nearly all general lighting service lamps now have "coiled" filaments. In preparing these filaments the tungsten wire is wound on a core (generally of steel) the diameter of which, according to the class of lamp, may be anything from three to six times the diameter of the filament. In order that the accuracy of the total length of wire in a finished lamp shall be comparable with that of its diameter, the mandril wire is controlled by exactly the same means as have already been described for the filament wire.

It is obvious that, as the size of the mandril wire is determined by its weight, care must be exercised in controlling the composition and density of the material from which it is made.

As a coiled filament is made by winding the tungsten wire on the mandril, it is necessary also to ensure that the hardness of the mandril wire does not vary over too wide a range. The reason for this is obvious; if a filament wire is being wound on a mandril having a diameter of about 0.005 inch, then if the tungsten cuts into the mandril on one occasion to a depth greater by 0.00001 inch than on another occasion, the length of filament wound on a definite length of mandril will be less by about 0.5 per cent.

The tolerances for mandril diameter are preferably even smaller than those for filament wire since the effect of an error of a given percentage on the final rating of the lamp is greater than that of a similar error in the diameter of the filament itself. The compensating effect mentioned in the previous section is obtained by winding the filaments falling towards the upper and lower limits of size on mandrils falling near their upper and lower limit of size respectively.

Within the limits mentioned, this compensating effect is nearly perfect, so that for a fixed length of helix the lamp efficiency, (that is, the ratio of light output to electrical energy input) remains constant although the filament wire may differ from the ideal size by 1.5 per cent.

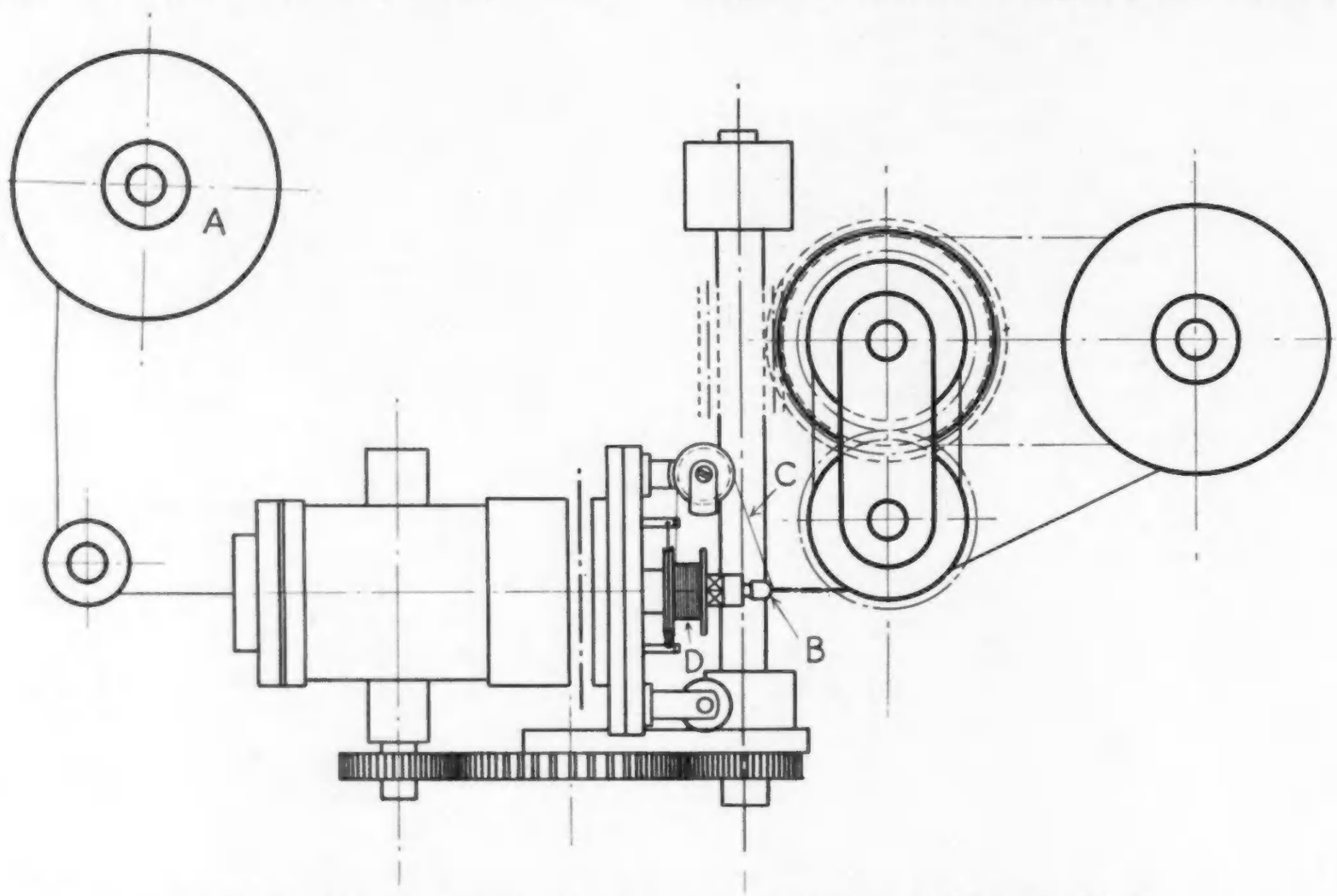


Fig. 5.—Diagram illustrating principle of the filament coiling machine.

COILING ERRORS.

We will now consider the operation of winding a filament on to its mandril. In this process lie potential sources of error additional to those described in the previous paragraphs. In the first place, a very high degree of precision has to be obtained in the distance between each turn of the coil. The designed distance between turns varies, according to the conditions imposed by the design of the lamp, from about 0.3 to 0.6 of the wire diameter, *e.g.*, the designed distance between the individual turns of a High Voltage 40 watt lamp filament is about 0.012 mm., that is, 0.0005 inch. The allowable systematic error in this distance between coils for gasfilled filaments is of the order of 1 per cent., that is, 0.00012 mm. ($5'' \times 10^{-6}$).

If fig. 5 is examined, in which the principle of the coiling machine is illustrated, it will be seen that the mandril wire A is pulled steadily through a sapphire nozzle B while the tungsten filament wire C, carried on the bobbin D, is rotated round it. Any variation in the rate at which the mandril wire is drawn through will therefore be reflected in errors in the pitch of the coil. In order to prevent this, a wide range of methods of controlling the rate of feed of the mandril wire has been devised and the design of coiling machines has not yet reached finality. Machines have also been constructed in which no mandril is used, and these have even been tested in regular production.

A second source of error arises from the fact that in coiling a fine wire on another having a diameter only 3 to 5 times greater, some stretching of the finer wire must necessarily take place. Therefore, the coiling machine must be designed and maintained so that the filament wire is wound on the mandril under conditions of constant tension. Failing this, wires originally having the same diameter will yield filaments of different lumen and watt rating when operated on the same volts because stretching reduces filament diameter and increases the pitch. The possible magnitude of the errors due to 1 per cent reduction in diameter has been already indicated in a previous section. An even worse effect may ensue if there is a spasmodic variation in the tension, since this will produce local reductions of diameter which will appear as "hot spots" on the filament of the finished lamp although the average rating may not be affected. At such points, even though the difference of temperature may be almost impossible to detect, the accelerated evaporation of tungsten will rapidly exaggerate the original defect and lead to early burn-out.

ERRORS IN CUTTING FILAMENTS, ETC.

The filament wire having being wound on the mandril it remains to cut the continuously wound length of coil into suitable lengths, to dissolve out the mandril and to apply any special heat treatments that may be desirable, before mounting the filament on the leading-in wires. All these processes again provide opportunities for errors to creep into the final rating of the lamp.

(1) It is obvious that a 1 per cent error in cutting the filament introduces a 1 per cent error in voltage rating for operation at designed efficiency, for at constant temperature the voltage on a wire is directly proportional to its length. Similarly, errors in mounting the filament may vary the effective length of the filament between the leading-in wires.

(2) The finished wire diameter of the filament may be affected by the process of dissolving out the mandril, particularly if the control of the wire drawing operation has not been completely satisfactory, since there may be oxide of tungsten on the filament which would be removed during the process of dissolving the mandril.

(3) Once the mandril is removed from the filament the coils, particularly in the fine sizes, are very easily distorted, so that, however much care has been taken in winding the helix, its pitch can be seriously disturbed if the arrangements for handling the filaments are not specially cared for.

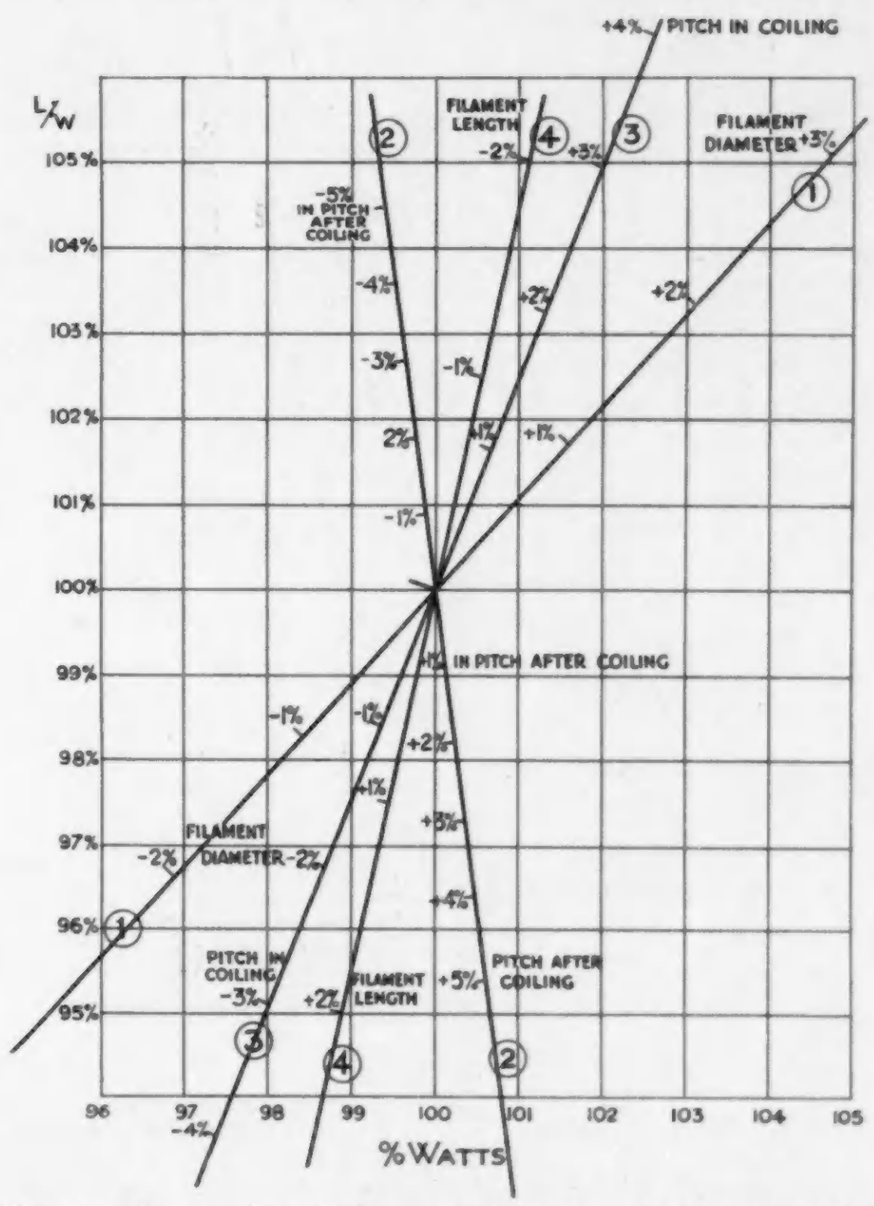


Fig. 6.—Errors in efficiency and watts at constant volts of gasfilled lamps arising from errors in filament dimensions.

EFFECT OF ERRORS IN FILAMENT ON LAMP RATING AT MARKED VOLTS.

In fig. 6 is shown a schematic arrangement which illustrates how errors in filament dimensions affect the current taken by a gasfilled lamp (High Voltage 40W to 100W), and its efficiency at a definite voltage.

The vertical co-ordinate indicates errors in efficiency and the horizontal co-ordinate errors in current or watts. The sub-divided diagonal lines on the diagram illustrate the following types of error :-* The line marked (1) indicates the effect

*NOTE.—Errors in filament dimensions of vacuum lamps produce similar errors in rating, but those arising from pitch errors are not so large as for gasfilled lamps. However, as the vacuum lamps are used in the lower watt ratings the filament diameters are smaller and it is more difficult to keep the errors small.

of an error in measuring the wire diameter or its equivalent. Errors in wire diameter may be due to the initial measurement, to variations in the amount of stretch which takes place in coiling, or to the amount of oxide or metal removed from it during the process of dissolving out the mandril. It will be seen that an error of 1 per cent in the wire diameter introduces approximately 1.5 per cent error in the current consumption and about 2 per cent in efficiency of the lamp. It is well to remember that the 1 per cent error in the rated diameter of a 40 watt filament corresponds only to about 0.00001 inch (10^{-5}).

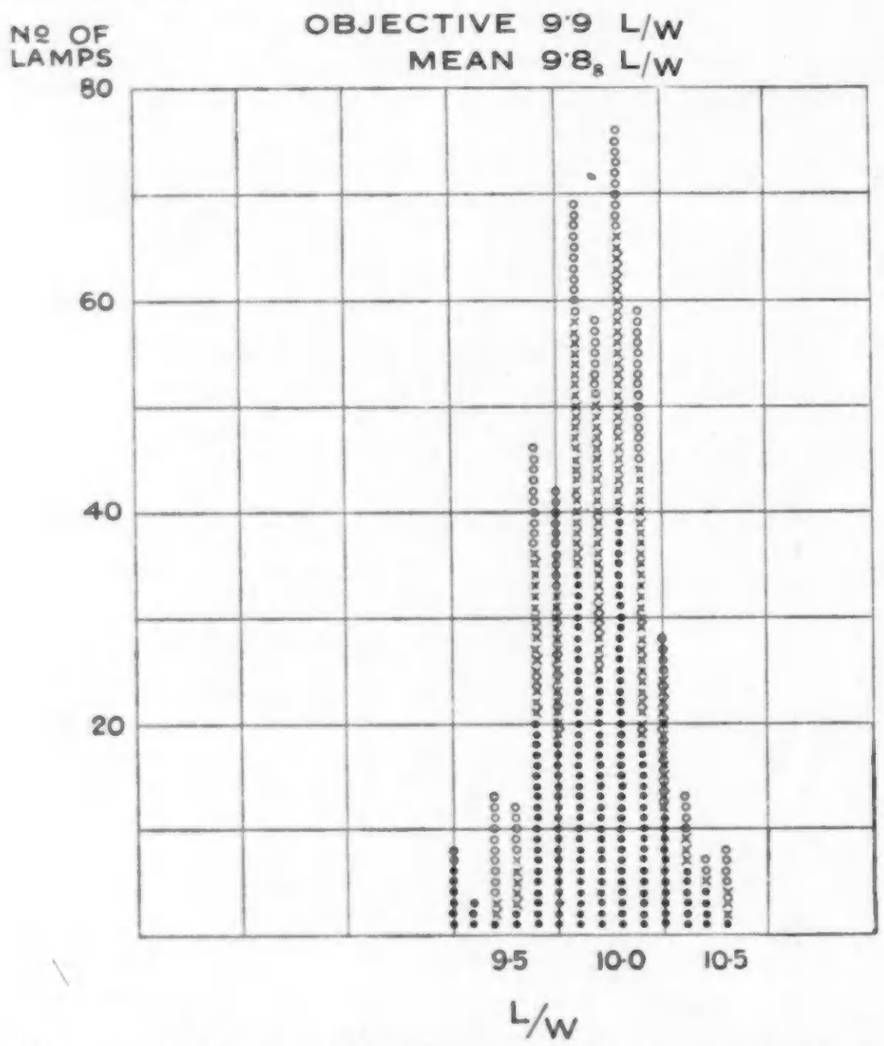


Fig. 7.—Rating results for HV 60W lamps made from the same batch of filaments mounted in lamps on different machines at different times, but utilising the same mounting operator. The signs indicate lamps made on different occasions.

Line (2) on the diagram indicates the magnitude of the errors introduced if the distance between turns is increased after correct coiling and filament cutting. There are a number of ways in which this may occur :-

1. By an excessive stress in the filament wire which is released on removal of the mandril.
2. By distortion of the filament in handling.
3. By varying amounts of "sag" occurring on first lighting up the lamp, arising out of variations in the original tungsten powder or from certain other causes.

It will be noted that a 4 per cent error in pitch, that is, an increase of 0.00006 inch ($6'' \times 10^{-5}$) in the pitch of a 40 watt lamp, introduces an error of approximately 0.5 per cent in current and nearly 4 per cent in efficiency.

Line (3) indicates the magnitude of the errors which can arise if the pitch of the coil as originally wound is incorrect. As already mentioned, this error can arise either in coiling, by variations in the rate of feed of the mandril through the coiling machine, or from errors in setting up the coiling machine (so that the relation between the revolution of the tungsten wire and the movement of the mandril is incorrect), or else from errors in the measured diameter of the filament wire. It is clear that if an error of 2 per cent is made in measuring the diameter of the wire, then the operator responsible for setting up the coiling machine will automatically introduce a 2 per cent error in the pitch.

By reference to the diagram it will be seen that a systematic error of only 2 per cent (0.00003 inch in a 40 watt coil) in the pitch when winding the coil introduces an error of about 3 per cent in the efficiency of the lamp. Irregularities in pitch, as distinct from systematic errors, lead to variations in temperature along the length of the filament and therefore reduce filament life apart from any variation in overall filament efficiency.

Line (4) on the diagram indicates the errors arising from wrong length of finished filament between leading-in wires. It will be seen that a 1 per cent error in the effective length of the filament introduces an error of over 2 per cent in efficiency and an error of 0.5 per cent in current consumed by the lamp. The main sources of this error are (1) errors in cutting the length of the coil, which can generally be kept below about $\frac{1}{4}$ per cent on filaments having a cut length of, say, 50 mm : (2) errors made by the mounting operator or machine, by which a varying amount of filament is subtracted from its active length in making the joints to the leading-in wires : (3) bad positioning or shape of the looped supports leading to variations in the cooling effect and therefore to a change in the effective operating length of the filament : (4) variations in effective mandril diameter.

A diagram of errors similar to that here described can be used to study statistically the results of photometric measurements made on considerable batches of lamps and so to estimate the source or sources of the deviations found.

Apart from the question of filament dimensions, there are two other closely associated factors which can appropriately be mentioned here. The first is the surface condition of the filament, any change in which must change the emissivity of the filament, and this involves changes in current and efficiency on constant volts. Secondly, the composition and pressure of gas in a gasfilled lamp can lead to errors in rating but, as indicated earlier, it is not possible in the space available to deal with all these matters in detail. It is sufficient to say that the control of these factors to avoid errors in rating of less than

1 per cent does not present such difficult problems as the control of the filament dimensions which have just been discussed.

Before finally leaving the question of filament dimensions it will probably be of interest to refer to the degree of accuracy that is achieved daily in a modern lamp factory, and fig. 7 shows the spread in the efficiency at designed volts of a large batch of lamps made from the same batch of 60 watt filaments. Those made on different assembling units are represented by different signs. These lamps were not all manufactured on the same machines or on the same day; the only common factor is the wire from which the filaments were made and the filament mounting operator. It will be seen that the batches of lamps made on the various occasions have closely the same degree of spread in efficiency.

It is usual to measure the spread in efficiency by the standard deviation of the observations. (The square root of the average of the sum of the squares of the deviations of each individual lamp from the mean of the batch). About 70 per cent of the batch of lamps will fall within a band of efficiency equal to ± the standard deviation.

In estimating the actual spread in efficiency of the lamps it is necessary to remember that there are errors in photometry involved in the measurements. It is known that if the same lamp were photometered several times on each of several days the standard deviation for such measurements would be about ±0.8 per cent.

The corrected standard deviation in rating of the lamp shown in fig. 7 is ±2.5 per cent. This spread in efficiency is equivalent to ±1 per cent spread in volts.

In an attempt to estimate the effect of variations introduced by the operation of filament mounting, filaments made from the same wire were issued equally to 15 different operators on 4 different occasions. On each occasion the lamp manufacture was completed at the same time on the same machine. The results are plotted in fig. 8. The corrected standard deviation of the rating is increased to closely ±3.0 per cent.

In the light of what has so far been described, it is not surprising that it is not generally found possible exactly to repeat these excellent results starting from a different wire, and in general practice, neglecting occasional errors arising from ordinary human failings, the output of a lamp factory consists of a mixture of batches, each one showing the close agreement indicated in the diagram just referred to, but with the centre lines for the various batches displaced from 1 per cent to 1½ per cent from the objective.

The effect of the combination is to give the result illustrated in fig. 9 where the results of measurements on lamps taken regularly each day from each unit producing lamps during six months are shown plotted. The corrected standard deviation of the rating is ±3.5 per cent. In this diagram the results are expressed in terms of the objective efficiency, as the standard efficiency for 60 watt lamps is not constant for all voltages of 200 to 250; (See British Standard Specification No. 161).

It has already been indicated that many of the factors are still receiving the urgent attention of lamp engineers but when it is remembered how

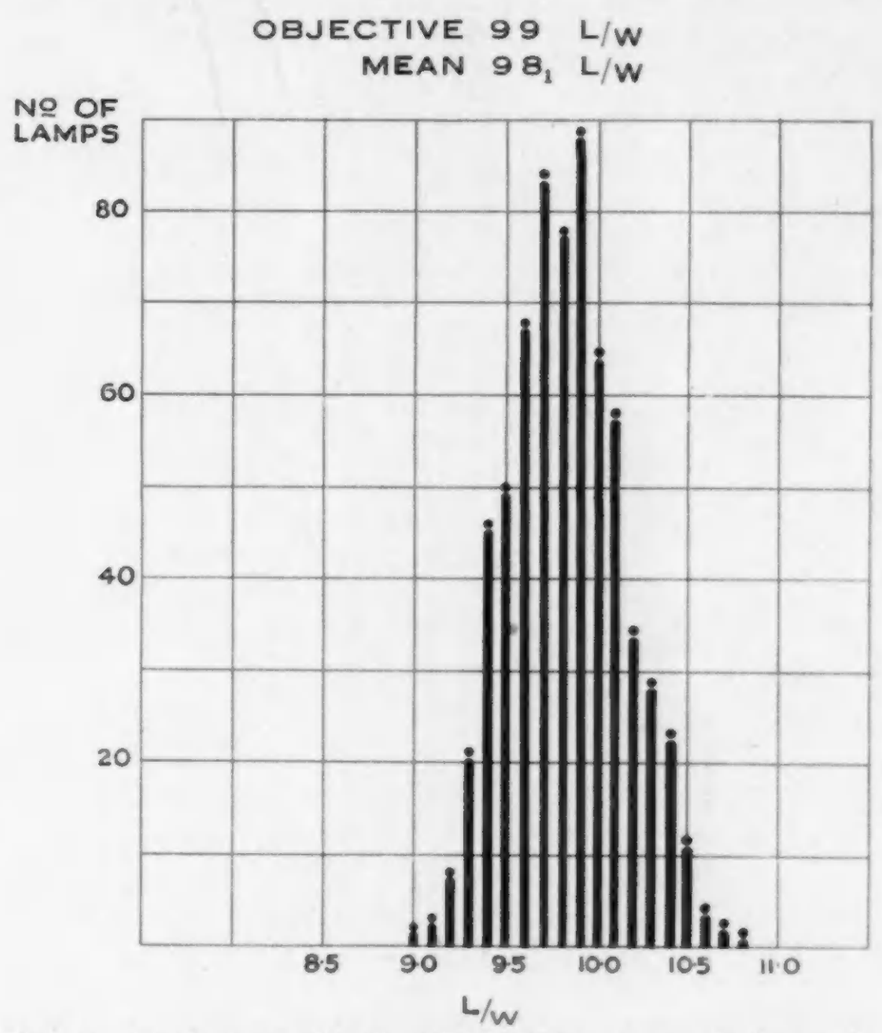


Fig. 8.—Rating results for HV 60W lamps made from the same batch of filaments issued in equal quantities to fifteen different mounters on four different occasions.

small are the errors in physical dimensions which give rise to 1 per cent error in the final result, and that the various processes have to be carried out in the mass at rates up to 1,000 or more per hour on a single machine, it is clear that there is only limited opportunity for marked improvement in uniformity over that at present achieved.

LIGHT CENTRE LENGTH.

The attention given to the efficient utilization of light has steadily increased the importance of accurate positioning of the filament relatively to the fitting, and the "light centre length" (*i.e.* the location of the filament relatively to the lamp cap) is the most important lamp dimension affecting the design of these fittings. There appear to be conditions in which differences of only one or two millimetres in this dimension may be of importance.

It is proposed, therefore, to deal with the factors which influence this dimension in the

finished lamp. The considerations here are numerous and it is only possible in this connection to refer briefly to one or two of the characteristics of glass, this being the material which the lamp-making machines have to handle.

In fig. 10 (i) is shown diagrammatically the elements of the lamp placed in position ready for

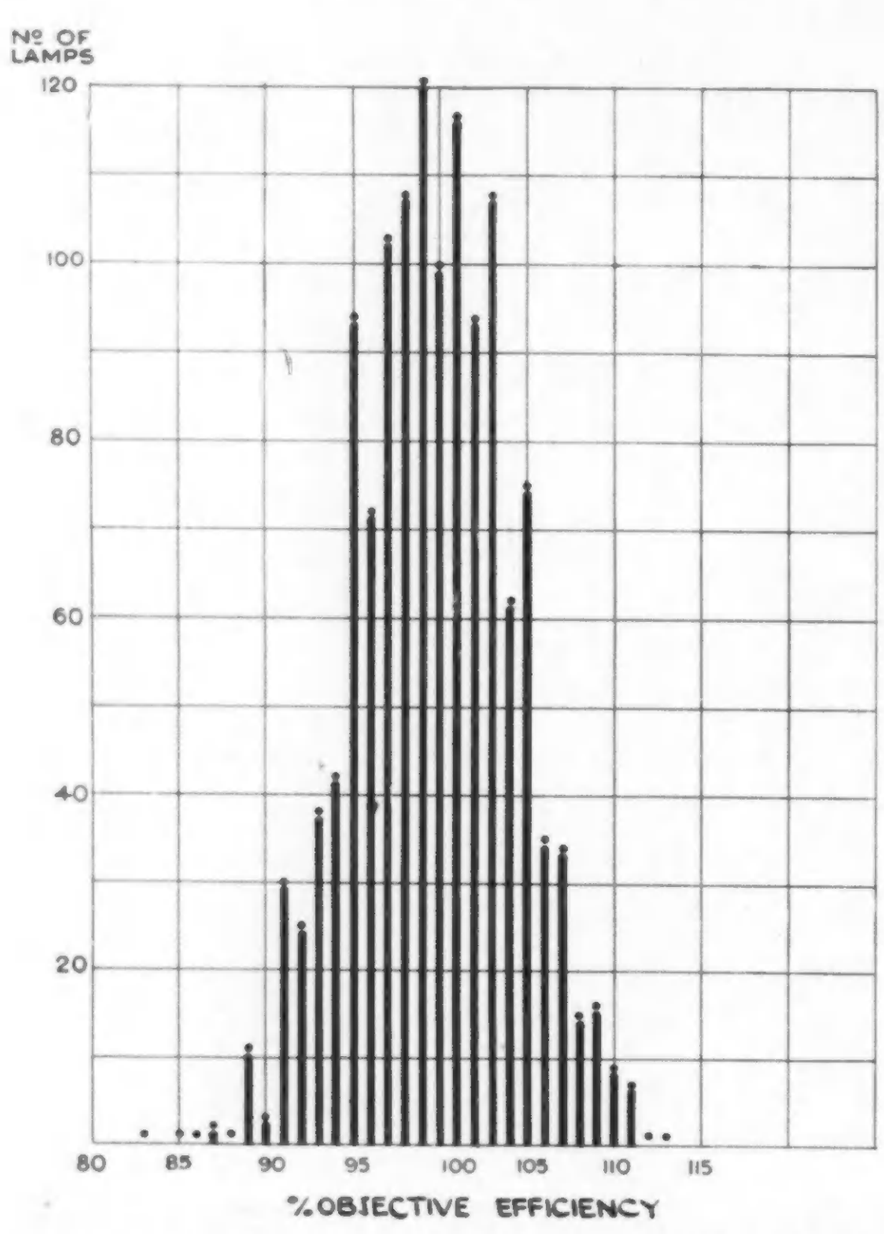


Fig. 9.—Rating results for HV 60W lamps taken regularly from all machines producing during the period January-June, 1931, inclusive.

assembly. "A" is a length of glass tubing of about 10 mm. diameter and 1mm. wall thickness, one end of which is opened out (or flanged) to form a collar to which the bulb will ultimately be sealed. "B" is a solid glass rod about 3.5 mm. in diameter into which the supports for the filament are inserted. "C" is the bulb as received from the glass works. "D" and "E" are the exhaust tube and leading-in wires respectively, and are not of prime importance in the problem under consideration.

Before considering the mechanical dimensions of these parts, let us first consider the working properties of glass. It is well known that glass softens as its temperature is raised and that in the region of red heat it is sufficiently plastic to be worked into almost any shape which the skill of the operator or machine can impose on it, but it is not generally realized that the fluidity of glass in this range doubles for every 15°C rise in temperature, and that it is also sensitive to slight changes in composition.

Glass used in lamp manufacture must, on the score of cost, be capable of being founded with reasonable ease; it must be stable when heated to temperatures in the working range, even when re-heated on more than one occasion; it must resist chemical attack when exposed to atmospheric conditions and, in the case of tubing and rod, have a high electrical resistance even at temperatures in the region of 400°C. The manufacture of glasses having these properties involves the use of certain materials, variations in the amount of which greatly influence the fluidity of the glass, hence very close control on the composition from this point of view alone is desirable.

In the older methods of melting glass in quantities of from 10 to 20 cwts. at a time in fire clay pots, this constancy was more difficult to secure than it is in the more modern methods where very large quantities are melted in tanks. However, the rapid change of fluidity with temperature is fundamental, and influences all glass working operations, so that a very high degree of precision has to be achieved if a definite rate of flow of the molten glass is to be attained. This property affects the distribution of the glass in the bulb, that is, the relative thickness of walls and neck both longitudinally and circumferentially; the uniformity in wall thickness of tubing and the uniformity in diameter of rod. The degree of accuracy secured can be estimated from the following data of the limits to which manufacture is successfully carried on.

Glass rod of diameter 3 to 4 mm. can be manufactured so that practically all the product can be utilized by grading into classes, the rod in any class having a range of only 0.2 mm. in diameter. Similarly, tubing 10 mm. to 11 mm. in outside diameter can be made so as to fall within 6 classes, the tubing in any one class having a range of only 0.5 mm. in diameter and 0.1 mm. in wall thickness.

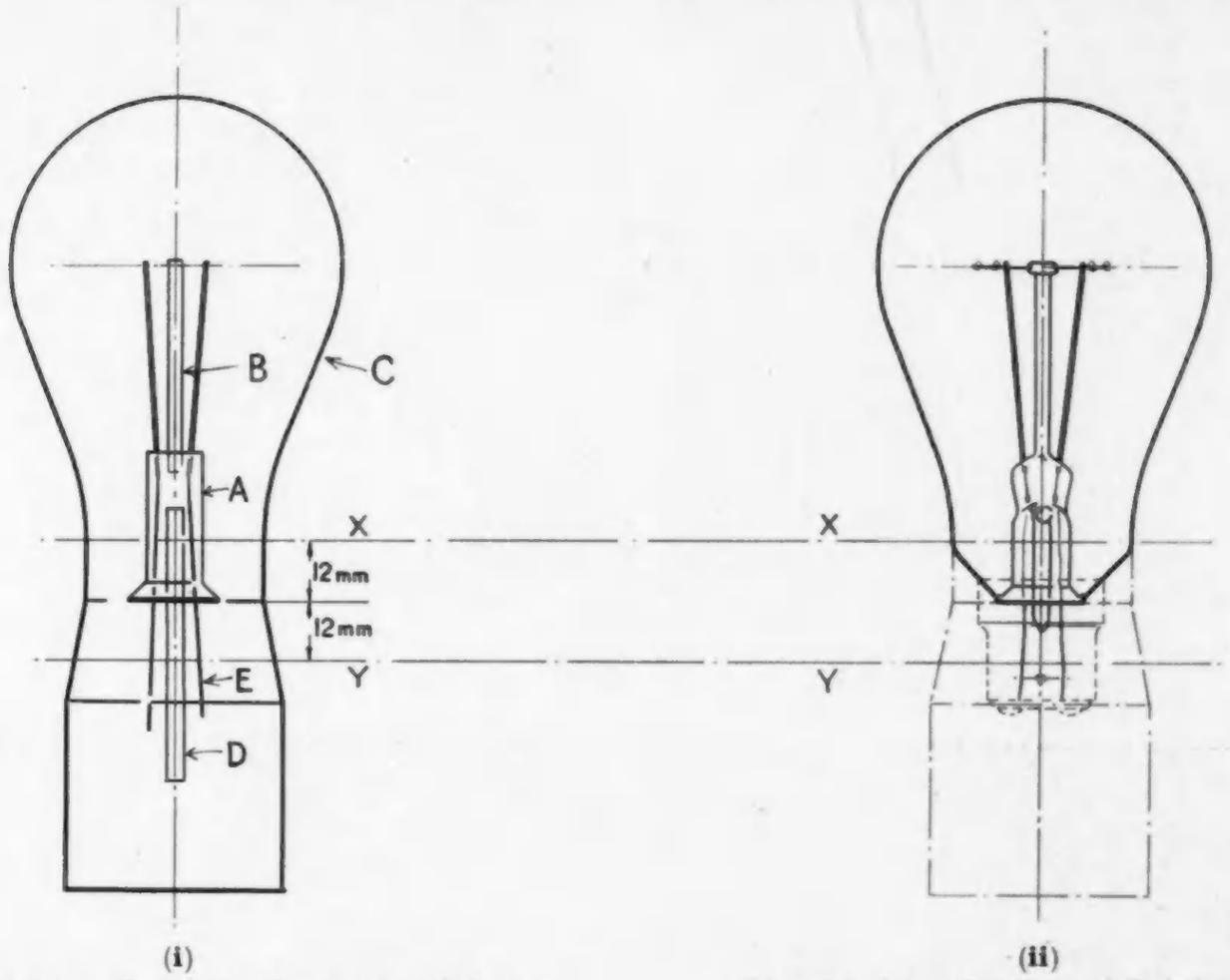
The specification for bulbs limits the total weight of the bulb to within ±15 per cent of a standard with over-riding restrictions as to the distribution and thickness of glass in the neck of the bulb within the zone lying between lines X and Y indicated in the diagram. The maximum thickness of glass round the neck of the bulb must not be more than 160 per cent of the minimum thickness and the maximum in any 90° arc must not be more than 130 per cent of the minimum, the minimum thickness allowable being 0.4 mm. It will be clear later what bearing these variations have on the light centre length of a finished lamp.

Turning now to the component parts, the tubing "A" used at one time to be cut into equal lengths and the flange formed on each short length with a

range of error corresponding to the variation in tube thickness. Considerable improvement has been effected by the introduction of automatic machines which first form the flange on the end of a 4 foot length of glass tube and then cut off a fixed length measured from the end of the flange, the operation being repeated until the complete length of tube is utilized. The rod, gauged to the limits already stated, is cut to within 0.2 mm. of a standard length.

In the next operation, the supports on which the filament will be mounted are fixed in the stud and the position of the filament relative to the flange is therefore finally determined. It is possible with the precautions here outlined to limit the error to less than 1 mm. on a length of 100 mm.

By far the greater proportion of the variations in light centre length arise, however, from the next operation in which the bulb is placed over the



(i) (ii)

Fig. 10 (i).—Diagram showing elements of lamp in position ready for assembly.

Fig. 10 (ii).—Outline of finished bulb.

The filament mount is assembled in a machine in which the position of the rod "B" relative to the flange "A" is mechanically determined to within about 0.2 mm., and while held in the machine, their adjacent ends are heated and moulded into the pinch through which leading-in wires pass. This assembled mount is next placed on a machine and the free end of the rod "B" heated and pressed up into a stud. The finished length of the mount from the base of the flange to the centre of the stud is determined by the amount of glass in the rod and the heating properties of the flames on the machine. This length will vary if the quantity of glass in the rod or the temperature of the flame varies appreciably. If the glass rod is too thin or the heating flame too hot, the glass is overheated, becomes too soft, and flows under its own weight tending to give a long or short length, depending on the type of machine used, or, on the other hand, if the glass rod is too thick or the heating flame inefficient, the length will be in error in the opposite sense and the stud is also liable to crack during the subsequent operations.

filament mount in a chuck on an automatic glass working machine, and is melted down on to the flange.

The full line in fig. 10 (ii), indicates the finished position of the bulb and the dotted line the original position of the bulb before the working operation. The exact shape of the bulb when finished determines the position of the cap relative to the filament and this shape depends on the distribution of the glass round the circumference of the bulb in the region XY, the weight of the glass below XY and the actual fluidity of the glass at the time of working and the position and nature of the flames. From what has been said before, the fluidity obviously depends on the intrinsic quality of the glass and the temperature to which it is heated in the flame. The temperature is mainly a function of the amount of glass heated, and the amount of gas and air supplied to the flames ; these must therefore be closely regulated. Finally, the actual shape and type of flame and the distribution of glass round the circumference of the bulb determine the finished size and shape of that portion of the bulb which is to form the seat of the cap.

The degree of accuracy obtained under modern conditions is such that it is possible to specify for all lamps up to 100 watt (in which the light centre length is 100 mm.) that an error greater than ±3 mm. shall not exist. Apart from the introduction of very much more complicated machines, it is difficult to see how a precision greater than this is to be achieved in the routine production of a somewhat complicated article, but lamp and glass making engineers still do not despair of designing machines which will make it possible economically to improve the precision in light centre length attained in manufacture.

With regard to the corresponding dimensions in bigger lamps it is generally found necessary to increase the tolerance approximately proportionally with the increased light centre length. To the ordinary engineer this might appear somewhat illogical as he would think it was not proportionally so difficult to manufacture an article 1 foot in length as it is to manufacture one 3 inches in length. The difficulties arise, however, from the fact that the large bulbs and the large tubing utilized in the bigger lamps are not required in anything like the same quantities as those used for standard lamps. It has therefore not been possible so to standardize production of these in the glass works as to get the same degree of precision as is obtained in the material for the smaller lamps, and the necessary precision in the glass making operations which would enable the errors of lamp making operations to be reduced, cannot therefore be achieved.

Floodlighting Marischal College, Aberdeen.

This famous college is now permanently floodlighted by G.E.C. floodlighting units and Osram lamps. The lighting installation was inaugurated during the recent International Illumination Congress held in this Country.

The Electrification of Caldercruix Paper Mills.

By R. E. KEELAN, A.M.I.E.E., M.I.M.E.E.
G.E.C. Resident Engineer, Glasgow.

AMONG the best known paper mills in the world are those owned by Robert Craig & Sons, which are situated near Airdrie, Scotland, at Caldercruix and Moffat. The firm has been engaged in the paper making industry for well over a century, and has established a very high reputation for many forms of paper, including blotting paper, manilla papers, duplex wallpaper, electrical papers and other specialities. The history of the undertaking is of a very fascinating character, and records show that the proprietors, whenever necessary, did not hesitate to scrap plant and equipment of an obsolescent character, in order that the mills should be equipped with the most modern machinery. It was therefore in accordance with the tradition of the firm that in 1927 a decision was arrived at completely to remodel the power plant of the Caldercruix Mills. A factor contributing largely to this decision was the need for reduced running costs in order to meet fierce home and foreign competition. Considerable investigation was necessary in order to ascertain how best the objects in view might be achieved, and it was about two years later (actually in November, 1929) that the contract for a most comprehensive electrification scheme was placed with The General Electric Co., Ltd. It should be recorded that the terms of the contract specified that the whole of the actual conversion work should be carried out during the fortnight of the summer holiday in 1930. This condition was duly fulfilled.

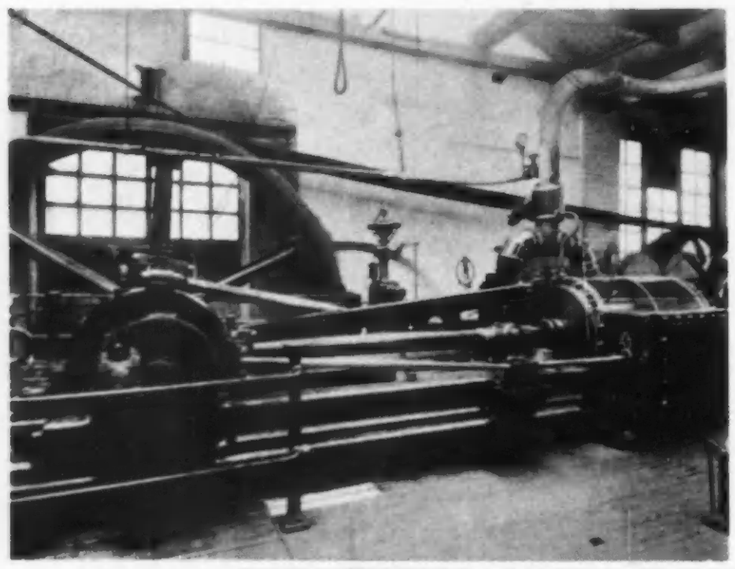
Fig. 1.—General view of Caldercruix Paper Mills.

Before proceeding to a description of the new power equipment of the mill, it is proposed to give a very brief outline of the processes involved in paper making, in order that the reasons for the types of power plant used may more clearly be appreciated.

The raw material is received in the form of either rags or wood pulp. The rags are received in bales and are first cleaned in dusters. A duster comprises principally a revolving wire cloth provided with spikes, the whole being encased in a stationary

chamber having a fan at one end. The rags are tossed about in passing through the cylinder and the majority of the dust and dirt present in them is removed in the air blast. Subsequently the material passes through the sorting house and the checking house, during which it is subjected to further cleaning processes prior to being placed in rag boilers where it is boiled with alkaline liquors. The rags are transferred from the boilers to breakers which reduce them from the small pieces in which they are received to a fibrous condition. The final process, before the "stuff" is taken to the paper machine, is performed by a beater which thins out the material into individual fibres by a tearing action. A group of beaters and breakers is shown in fig. 5.

If wood pulp be the raw material, before it is ready for the paper machine it is usually passed through a revolving boiler to be broken up (fig. 6) and then to kollergangs (fig. 7). A kollergang is a heavy type of edge runner mill consisting of a dish about 10 ft. in diameter, with a granite floor. Revolving vertically about their own axes in this dish are two granite discs 6 ft. in diameter, and 18 ins. thick, each weighing between 3 and 4 tons. The action of the kollergang is half tearing and half grinding. From the kollergang the material passes to the beater where it undergoes final preparation for the paper machine, and where it is dyed and sized.



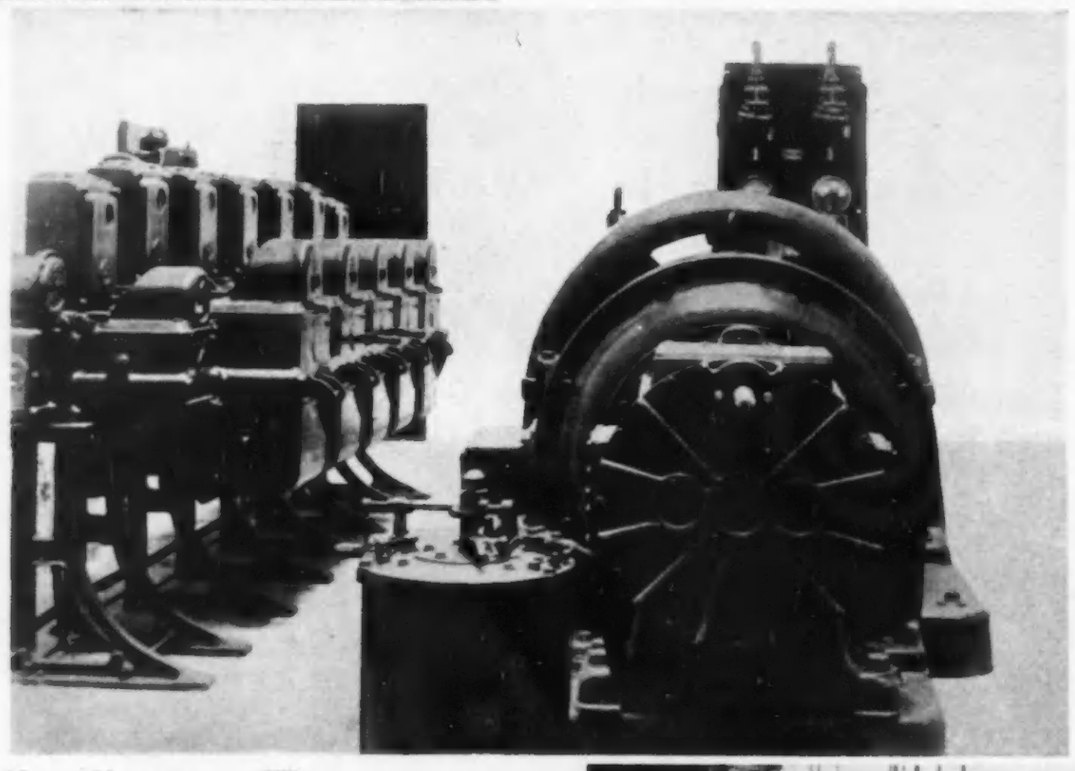


Fig. 2. (above) One of the old horizontal steam engines.

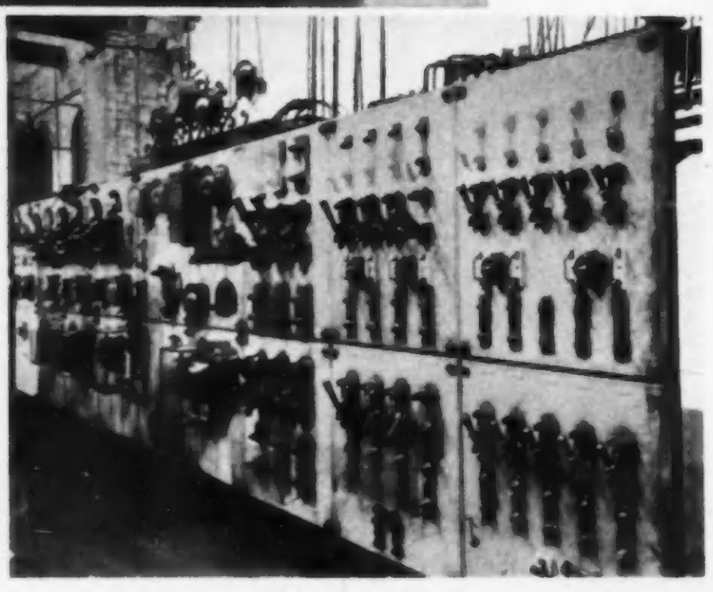
Fig. 3. (right) The old auxiliary power house.

Fig. 4. (below) The old D.C. switchboard.

These three illustrations are reproduced from photographs taken several years ago when the apparatus was first installed.

A paper machine is actually a series of rather complicated machines which concentrate the material from a thin liquid into a wet paste, and further, by means of a series of rolling operations convert it into rolls of paper. These rolls are conveyed to the super calenders where the paper is passed through a series of steam heated metal rolls with highly polished surfaces, alternating with compressed paper bowls; this process gives the desired finish to the paper. Subsequent operations consist of cutting, inspecting and packing.

At the time when the conversion scheme was decided upon, the three paper making machines contained in the mill, and other heavy duty machines were steam engine driven, the remainder of the machinery, such as the kollergangs and those employed in the rag departments and cutting and finishing departments, being driven principally by D.C. motors, and in a few cases by A.C. motors.



The boiler plant in the mill consisted of four Stirling boilers of the five drum type with super heaters and economisers, fired by class "E" underfeed stokers and working at 170 lbs./sq. in. with a final temperature of 500° F.

The beater mill drive, which up to that time had been regarded as the main drive, was effected by a Yates & Thom cross-compound horizontal

engine, rated to give 800 I.H.P. at a speed of 64 r.p.m., and geared to the main mill shaft which ran at 126 r.p.m. This shafting—about 300 ft. long—ran in old type grease lubricated bearings. Various countershafts of the same type were driven from this main shaft, through the medium of either belts or ropes. Such methods not only gave rise to the troubles that usually accompany belt and rope drives, but involved comparatively heavy lubrication costs.

Paper machine No. 1 was driven by a high speed vertical compound engine working at 160 lbs. pressure and exhausting into the machine drying cylinders. This was a modern unit erected in 1924. Certain difficulties in governing were presented due to the large range of speed variation required, which ranged from 16 ft. per minute paper speed minimum to 250 ft. per minute paper speed maximum; moreover a very close adherence to any set speed had to be maintained, as this factor constitutes a vital necessity in the manufacture of paper. Any variation in speed causes a corresponding increase or decrease in the weight of the paper being made.

Paper machines Nos. 2 and 3 were driven by horizontal two cylinder simple expansion engines, working at a pressure of 90 lbs. per sq. in. and exhausting into the drying cylinders of the paper machines. At times, according to the grade and type of paper being made, an appreciable quantity of steam had to be exhausted to atmosphere, and at other times compensating steam had to be provided direct from the boilers as make-up in the drying cylinders.

The two super calenders in the mill were driven by horizontal two-cylinder simple expansion engines exhausting to atmosphere, while heating steam for the calenders was obtained direct from the high pressure boilers.

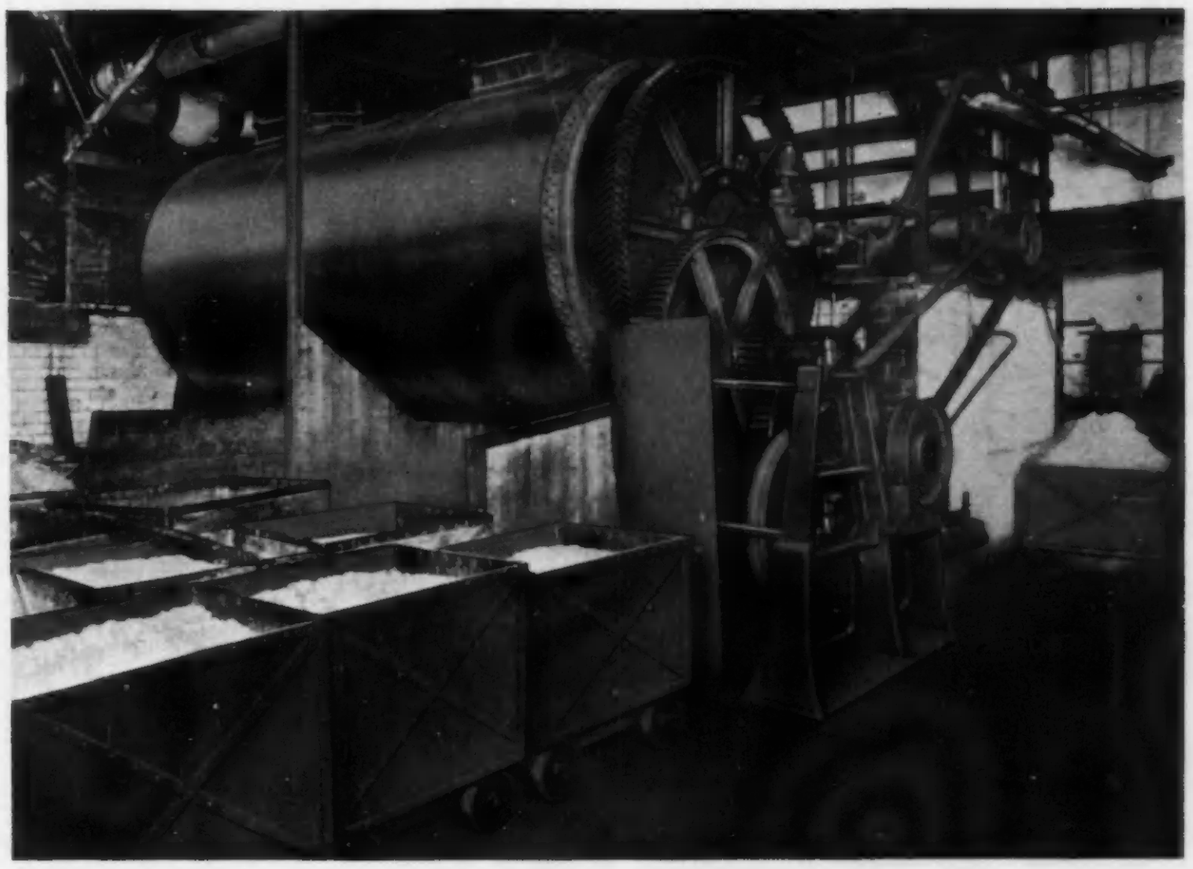


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Fig. 6.—Boiler for wood pulp.

Fig. 5.—A group of beaters and breakers belt driven by motors in the basement (see fig. 17).

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The supply for the direct current motors was obtained from a generating set consisting of a vertical high speed triple expansion condensing engine driving a 500 kW D.C. generator through ropes. Alternating current was obtained from the local supply company.

From the foregoing description of the power plant as it existed before the conversion, it will readily be understood that there existed plenty of scope for effecting economies, particularly when it is borne in mind that the direct current supply was being generated by a set taking 32 lbs. of steam per kW hour. Further, it was found that the direct current motors would soon need replacement, and that the cable was in a condition which would necessitate early renewal.

As a preliminary step to conversion, three 110 h.p. drip-proof A.C. motors were installed to drive a section of the beaters. The result of the trial of this drive gave complete satisfaction. Before a final decision could be reached as to the extent of the conversion and the type of plant which should be installed, however, it remained to determine

whether power could be obtained from the local supply authority at such a rate that, when its cost was added to the cost of generation of process steam, the total would be less than that which could be obtained by the installation of a pass-out turbine for electricity generation and the provision of process steam. The result of the comparison made showed

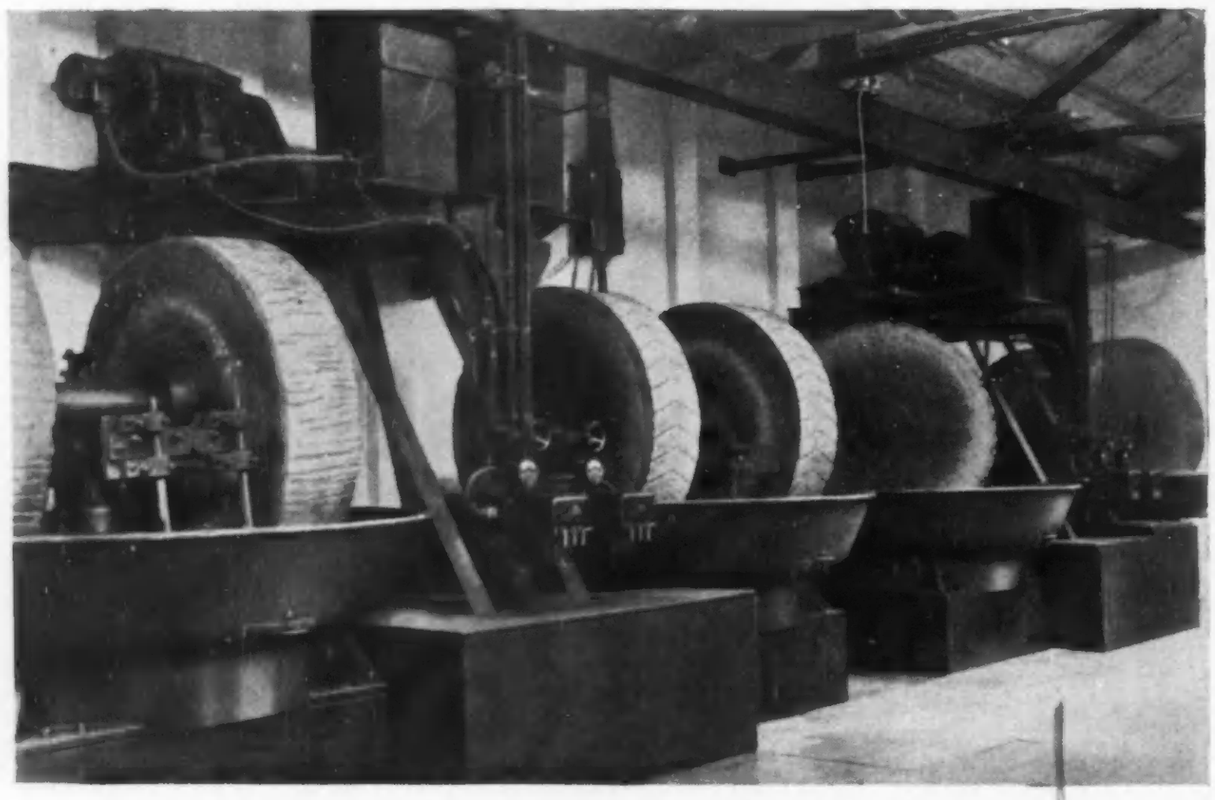

Fig. 7.—A group of kollergangs, belt driven by 25 h.p. motors mounted on wall brackets.

that the use of a pass-out turbine would undoubtedly prove more economical and the scheme, therefore, as put in hand included a pass-out turbo-alternator, together with main and auxiliary switchgear, A.C. motors for the whole of the drives in the mill (apart from Ward Leonard controlled machines) new cabling, etc.

It was decided to retain the existing boilers, super heaters, and economisers, but the class "E" underfeed stokers were replaced by underfed chain grate stokers of the "L" type, with a view to ensuring as high an overall efficiency as possible from the steam generating plant.

It was further decided to adopt the same system as that employed on the Grid for low tension operation, namely, 440 volts, 50 cycles, 3 phase, so as to simplify matters should the occasion ever arise for taking power from the national supply at a later date. The turbo-alternator set (fig. 8) is rated at 1750 kW at a speed of 3,000 r.p.m. The turbine is of the impulse, multi-stage, pass-out type, working at a stop valve pressure of 165 lbs. per sq. in. with a steam temperature of 500° F., and is arranged to pass out up to 20,000 lbs. of steam per hour at 20 lbs. per sq. in. gauge. It is suitable also for operating at a future date at a steam pressure of 250 lbs. per sq. in. gauge and 500° F. total temperature. The turbine works in conjunction with a Mirrlees Watson Delas Ginabat surface condenser, capable of dealing with 18,500 lbs. of exhaust steam per hour and maintaining a vacuum of 28½ ins. under these conditions with the barometer at 30 ins. when supplied with circulating water at 70° F. This size of condenser was adopted so as to meet the conditions arising out of a very low demand for pass-out steam and a high demand for electrical power, circumstances which would necessitate the condenser dealing with practically all the steam required by the turbine. An Arca reducing valve is fitted for reducing the boiler pressure of 170 lbs. to 20 lbs.—which is the pass-out pressure—for the purpose of heating up paper machine drying cylinders and for other requirements before the turbine is started, a condition which naturally arises early every Monday morning prior to the continuous run for the week. Suitable steam meters are also installed for the purpose of providing a continuous check on the steam consumption.

The turbo-auxiliaries are all electrically driven. Careful consideration had to be given to the supply of circulating water for the condenser, the nearest available point being the mill pond (fig. 9) which is situated about 350 ft. from the turbo house. The pond itself is fed from a mountain stream in the

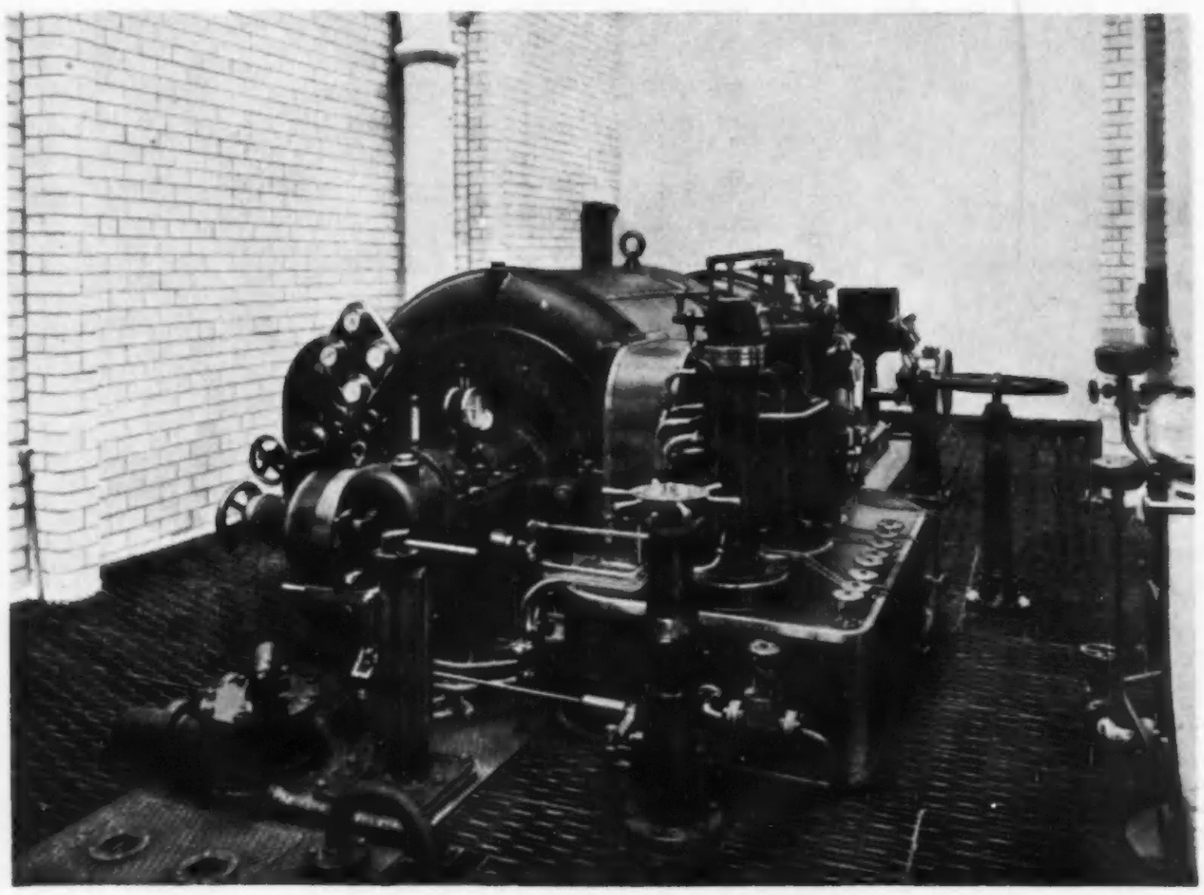

Fig. 8.—1750 kW, 3,000 r.p.m. pass-out turbo alternator in the power house.

locality. In the event of failure of the circulating pump, an alternative source of cooling water is provided by gravity from a point at a higher level, capable of supplying circulating water for short periods. In both cases the discharge goes into the lower mill pond.

The turbine is direct coupled to a 3 phase, 50 cycle, 440-volt alternator. The alternator field is supplied from a direct coupled overhung multi-polar exciter, and is arranged with a closed system of air cooling by the Premier Engineering Company.

The main switchboard (fig. 10) is in a room immediately adjoining the turbine house, and is built of slate panels stayed from the wall with expanded metal doors at each end. One panel is equipped for the control of the alternator, and six for feeder circuits which supply power for lighting and for the motors in the mill. There is also a blank panel for equipment to control a second turbo-alternator which it is hoped to install at a later date. The equipment for controlling the feeder circuits is on standard lines, but an interesting feature in connection with the control of the alternator should be noted. Owing to the heavy current, two

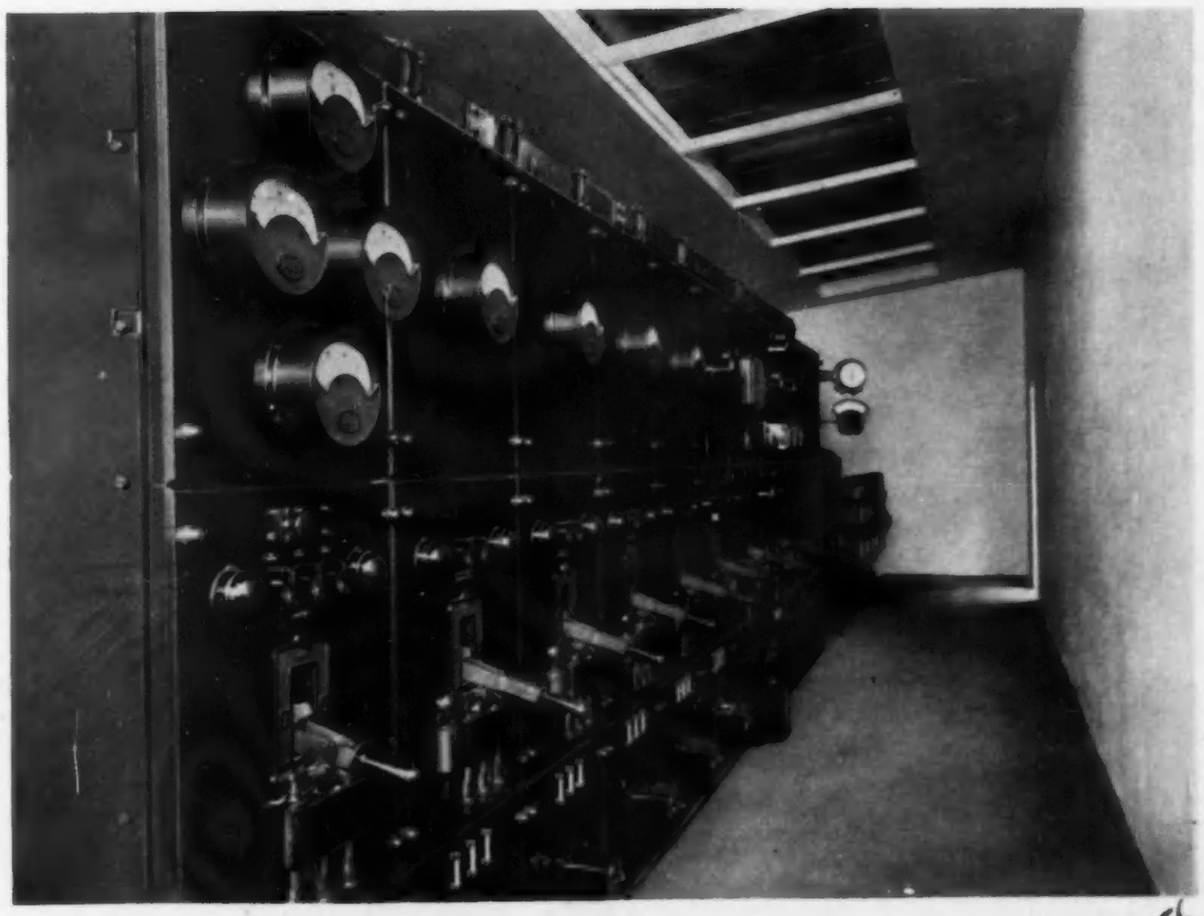

Fig. 10.—Main switchboard.

1500 amp. oil circuit breakers are employed in parallel and these are electrically interlocked in such a manner that by means of a time lag both breakers are always either closed or open; if after closing one switch, the second is not paralleled within a predetermined time, the first trips out.

The busbars of the main board are connected to existing metalclad switchgear (seen on the extreme right of fig. 10) which controls further feeders.

The principal auxiliary switchgear consists of oil immersed pedestal switch units as shown in fig. 19. The cable from the main board to these units is of the paper insulated, lead covered and armoured type. The further detail of the distribution is in accordance with standard modern practice.

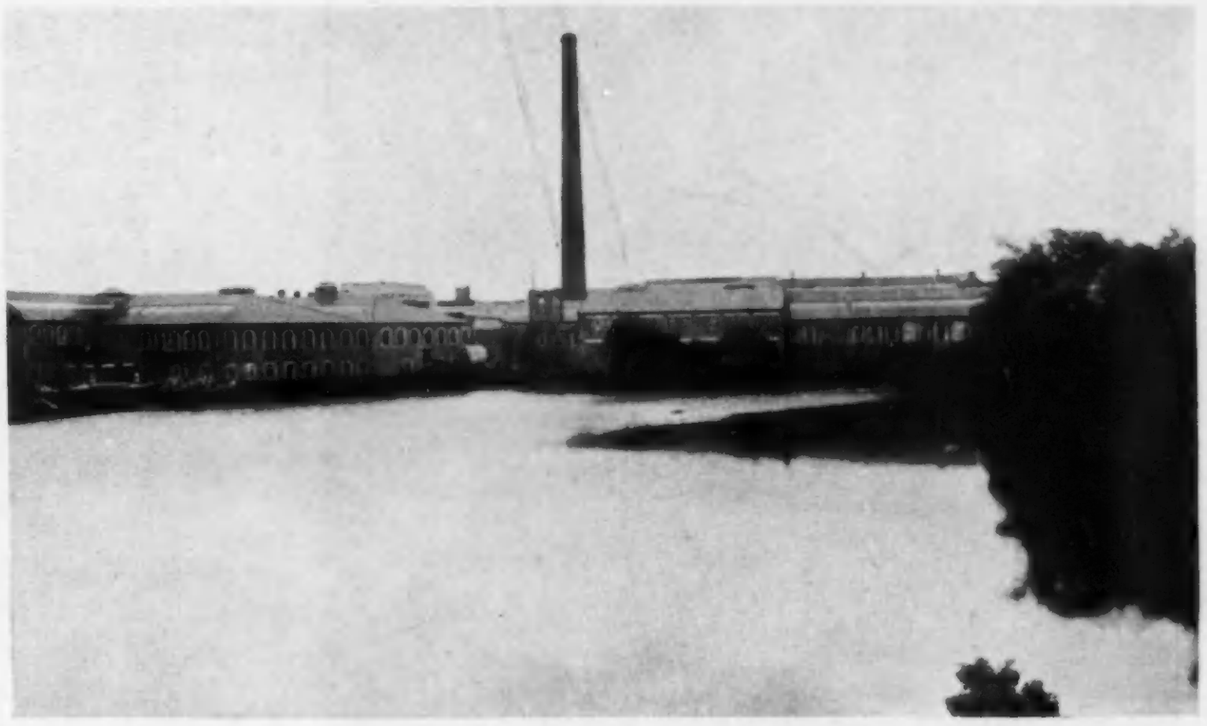

Fig. 9.—Mill pond for cooling water supply with works in the background.

It has already been stated that the re-equipment of the mill included the installation of new motors. In all 70 have been provided with total capacity of over 1,000 h.p., ranging in outputs from 1¼ h.p. to 120 h.p. The most interesting drives are those for the paper machines, super-calenders, and beaters and breakers.

From the point of view of driving, the operations in the paper machine are divided into two main sections (1) a constant speed section at what is known as the wet end, consisting of agitators, pumps, strainers, etc., and (2) a variable speed section which performs the actual forming of the paper.

For driving the constant speed section of the machine a standard slipring induction motor is coupled direct to the backshaft of the paper machine.

In considering the best system to employ for the driving of the variable speed section of the machine, the most important point which had to be

taken into account is that the range of speed required is very wide. Further, when running at any pre-determined speed, it is necessary that this speed should be maintained constant. Any variation from a pre-determined speed would be liable to cause variation in quality or weight and in some cases might give rise to breakages. For these reasons it was decided to install the Ward Leonard system of control in preference to employing variable speed A.C. commutator motors. Considerable success has attended the installation of the Ward Leonard system, because the constancy of speed and sensitive variation obtainable have given the machine-man a high degree of control over the processes involved; further the creeping speed of the Ward Leonard system is very advantageous.

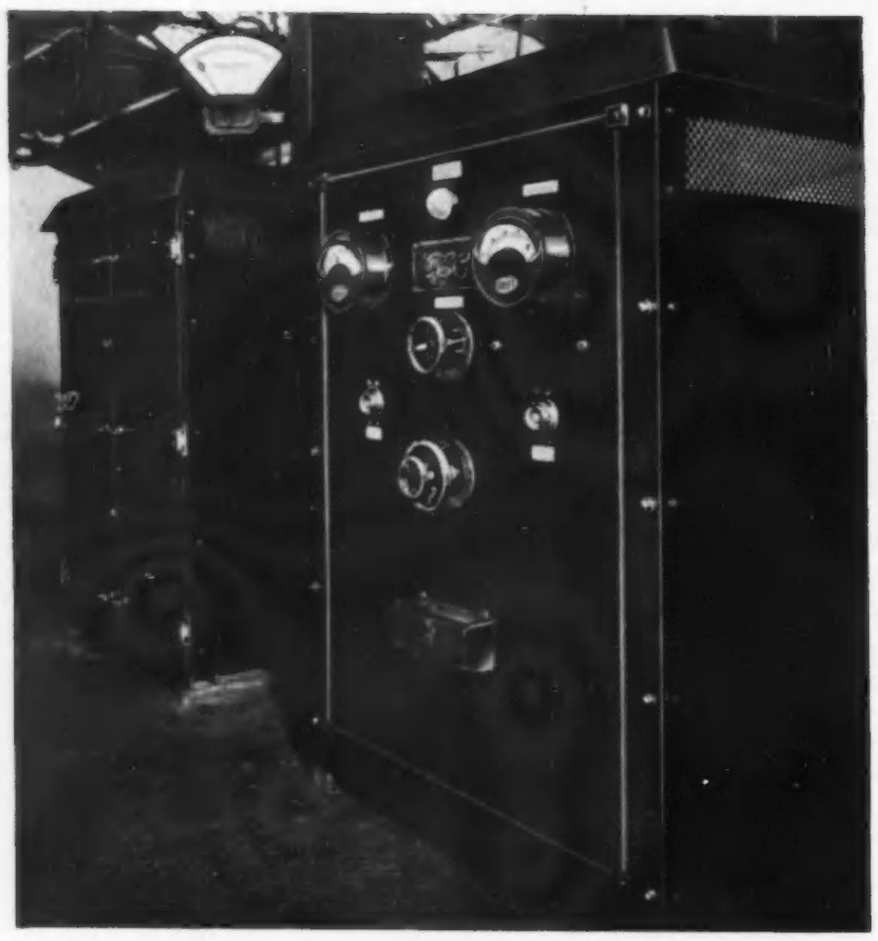

Fig. 11.—Main control cubicles for paper machines Nos. 1 and 2.

The three paper machines are driven by main motors whose ratings are as follows:—

(1) 18/88 h.p. at 78/1150 r.p.m.
(2) 22/110 h.p. at 68/1000 r.p.m.
(3) 16/60 h.p. at 83/830 r.p.m.

The equipments are entirely similar apart from the variation in rating. Illustrations from various points of view in the paper making machine room are given in figs. 11, 12, and 13, while the control methods employed are shown in the diagram fig. 12 which should be referred to in conjunction with the following description.

The main motor is a totally enclosed direct current compound wound machine designed for external ventilation by means of an electric fan mounted on the top of the motor, as shown in fig. 12. The shunt field of the motor is arranged for separate excitation. The series winding is in circuit at higher speeds in order to ensure stability, but at lower speeds it is automatically short circuited.

The machines comprising the motor-generator set are of standard design.

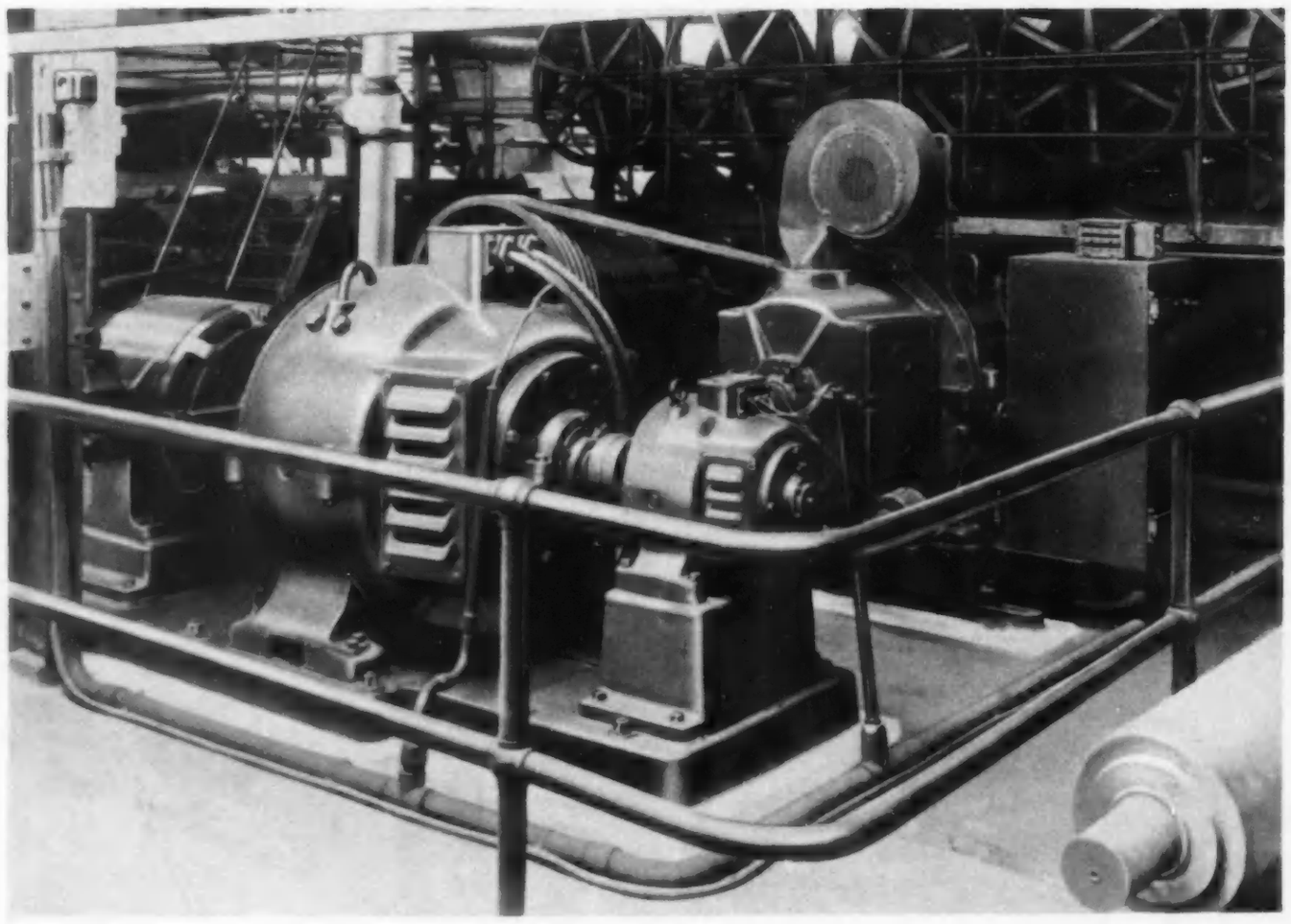

Fig. 12.—Main motor and Ward Leonard set for paper machine No. 1.

The principal control apparatus is contained in a sheet steel cubicle, as shown in fig. 11. Within the cubicle are mounted three regulators, namely, the main regulator, a vernier regulator and the

regulator for the exciter of the motor-generator set. On the outside of the cubicle are mounted the following :—

Ammeter for the main armature circuit of the main motor.

Voltmeter for the exciter of the motor-generator set.

Indicating lamp for ventilating fan.

"Stop" and "Start" push buttons.

Fuses.

Handwheels for the regulators. The handwheels for the main and vernier regulators are mounted concentrically.

In addition to the main control cubicle, there is a local control cubicle mounted on the motor bedplate, as shown in figs. 12 and 13. This contains the following apparatus.

Contactor type circuit breaker for main armature circuit.

Contactor for short circuiting series field.

Contactor for inserting resistances in the shunt field and operating in conjunction with series field contactor.

Overload relay.

Contactor type direct starting switch for fan motor.

The motor of the Ward Leonard motor-generator set is started by an oil-immersed rotor starter in conjunction with a triple pole oil circuit breaker in the stator circuit. This breaker is fitted with overload and no volt features and is interlocked with the rotor starter so that the starter handle must be returned to the "off" position before the induction motor can be started.

When it is desired to operate the paper making machine, the Ward Leonard motor-generator set is first started and brought up to speed by means of the rotor starter. The exciter voltage builds up and its rheostat may be adjusted to the desired voltage. The contactor in the main motor armature circuit is then operated by the push button switch, provided that the main rheostat is in the "off" position. The speed of the paper machine may then be adjusted to any desired value within its range by means of the main rheostat. At a certain point on the main rheostat full generator voltage is attained, and weakening of the motor field begins. The series winding is then cut into circuit by the opening of its short circuiting contactor. Simult-

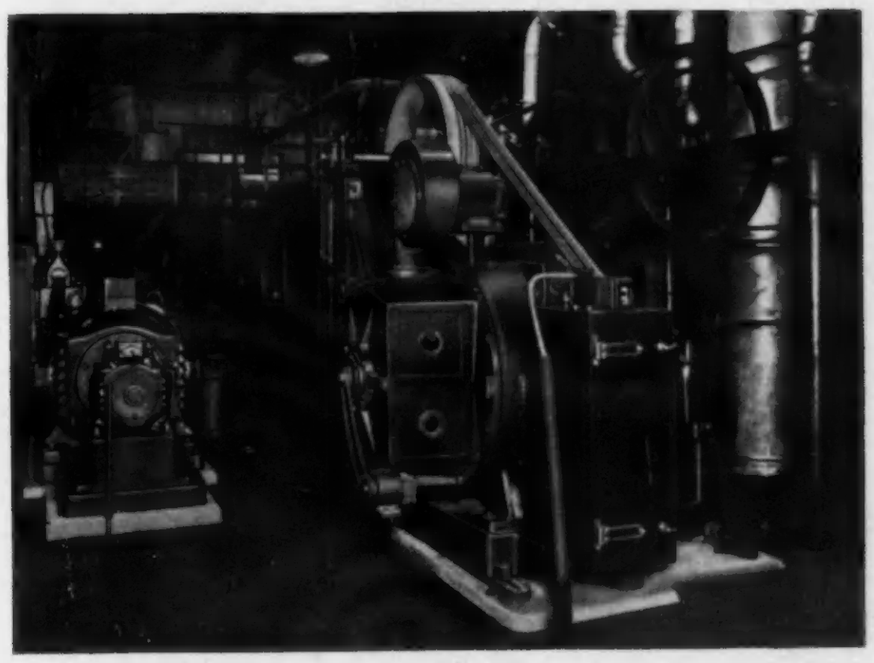

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Fig. 13.—Main motor and Ward Leonard set for paper machine No. 2, showing local control cubicle mounted on bedplate of motor.

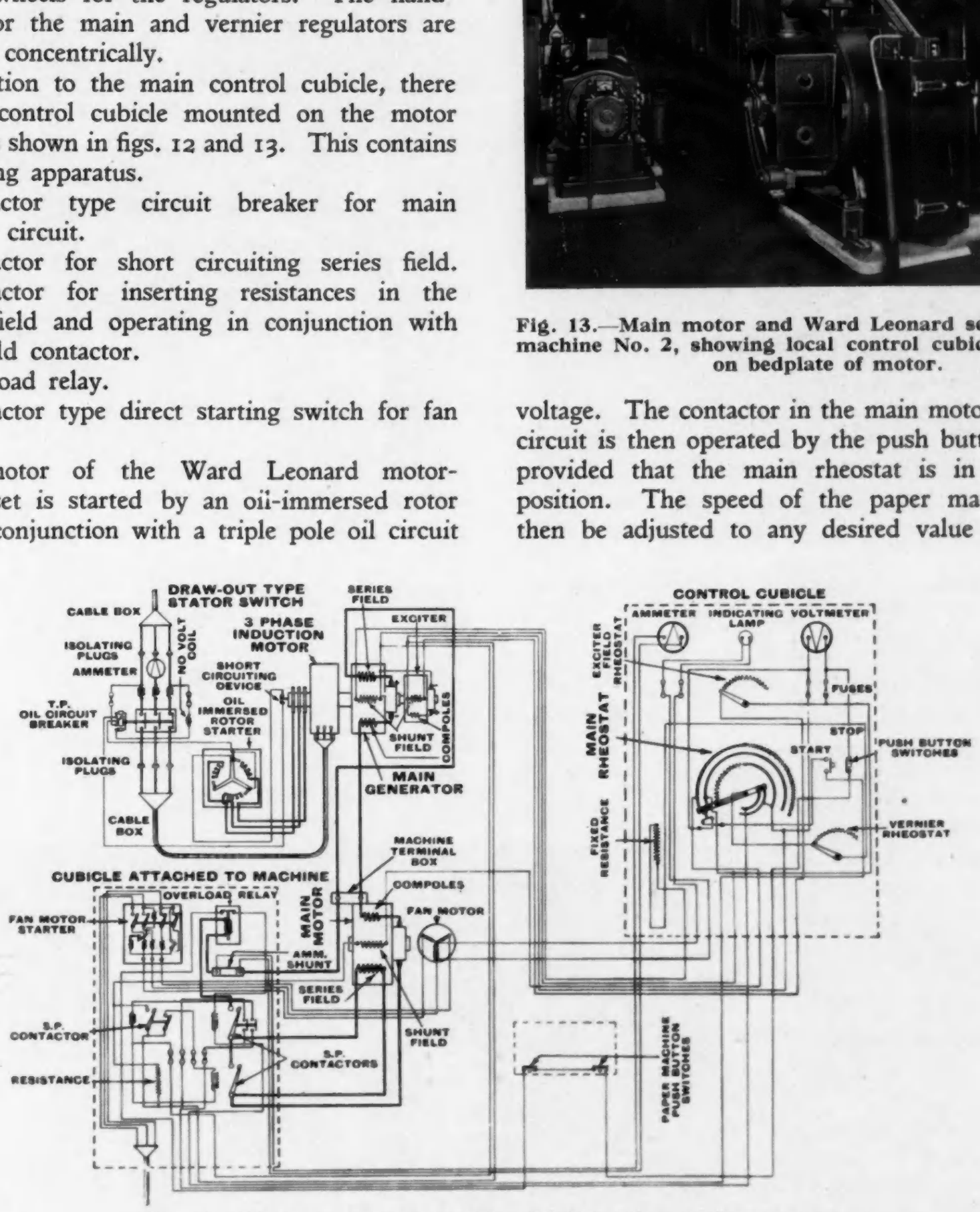

Fig. 14.—Diagram of paper machine driving and control apparatus.

aneously the series compensating contactor in the shunt field also opens and inserts a resistance in the motor field circuit. The resultant effect is that the total ampere turns and flux of the field are un-

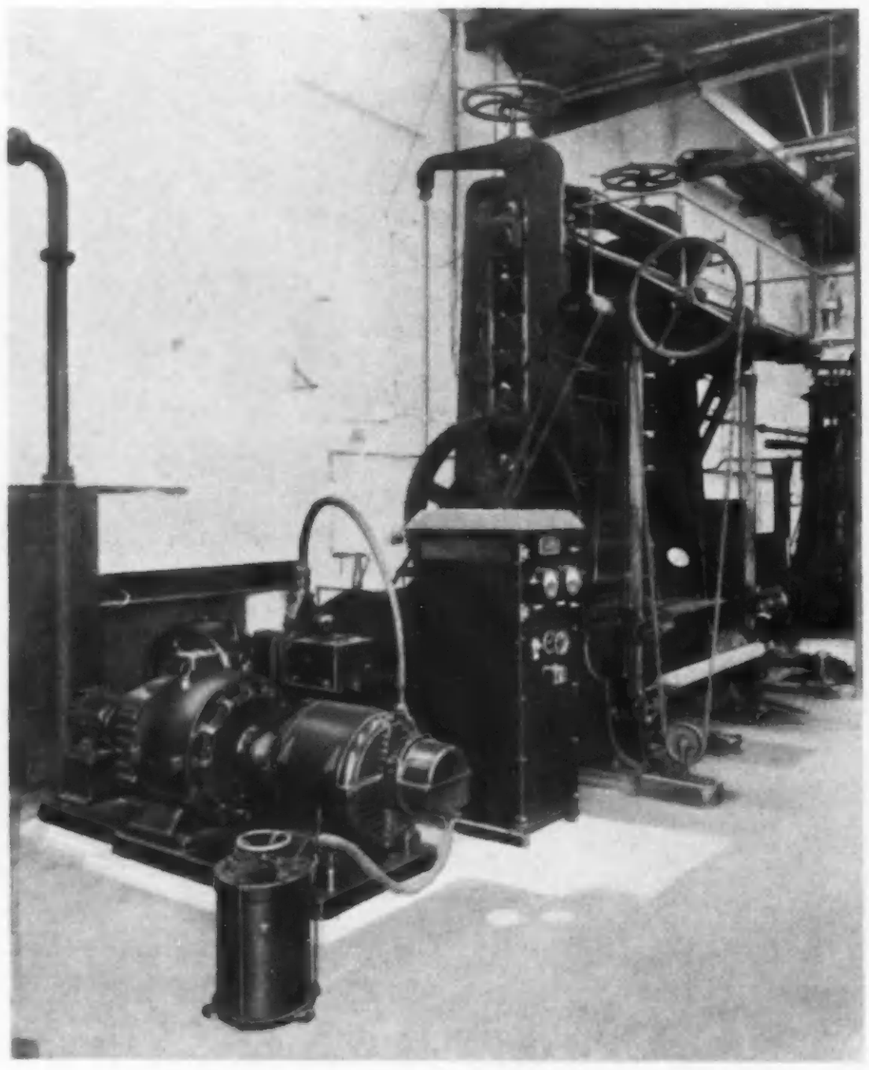

Fig. 15.—12-bowl super-calender with main motor (partly seen), Ward Leonard set and control gear.

altered, and the series winding has therefore been switched on without any fluctuation in speed. This is a most important consideration in the operation of a paper machine.

The equipment may be stopped by pressure of "Stop" buttons either at the control cubicle or at various points on both sides of the paper machine. These cause the main armature contactor to open and interrupt the armature circuit; thus the machine can be stopped immediately in case of emergency. The contactor cannot be reclosed until the main rheostat has been returned to the off position.

The driving of the two super-calenders (see figs. 15 and 16), is also carried out upon the Ward Leonard control system. The detail of the control varies but little from that described above in connection with the paper machine drive, the principal difference being that, as the speed control of the machines need not be so fine, a vernier regulator is unnecessary; also no provision is required for short circuiting the series field of the main motor. Another point of difference is that there is no local control cubicle, all the necessary apparatus being contained in the one control cubicle.

The motor driving the 12-bowl super calender is rated at 16½/80 h.p. with a speed range of 102/980 r.p.m.; that driving the smaller calender is rated at

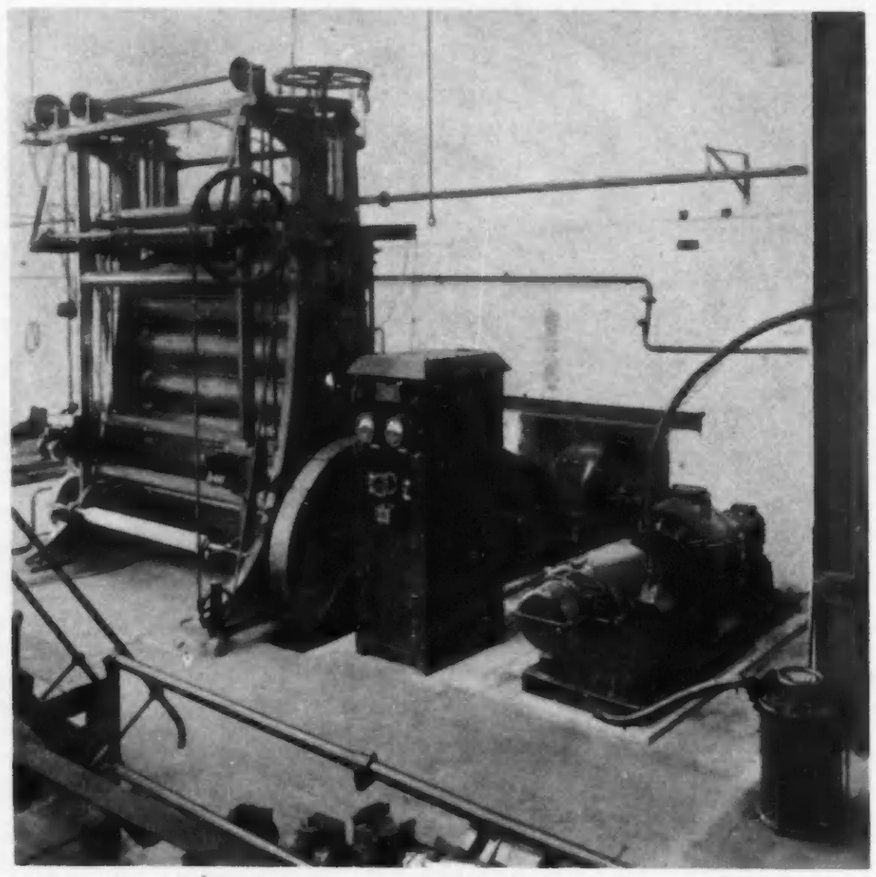

Fig. 16.—Smaller super-calender with main control cubicle, main motor and Ward Leonard set.

11/16 h.p. with speed range of 76/760 r.p.m. Both these motors are of the open type and drive on to the main calender shaft through the medium of a chain in an oil bath. The speed variation is very wide; in the case of the larger calender it varies normally from 30 feet per minute to 270 feet per minute, while creeping speeds down to 2 feet per minute are available for use when a new reel of paper is being led through.

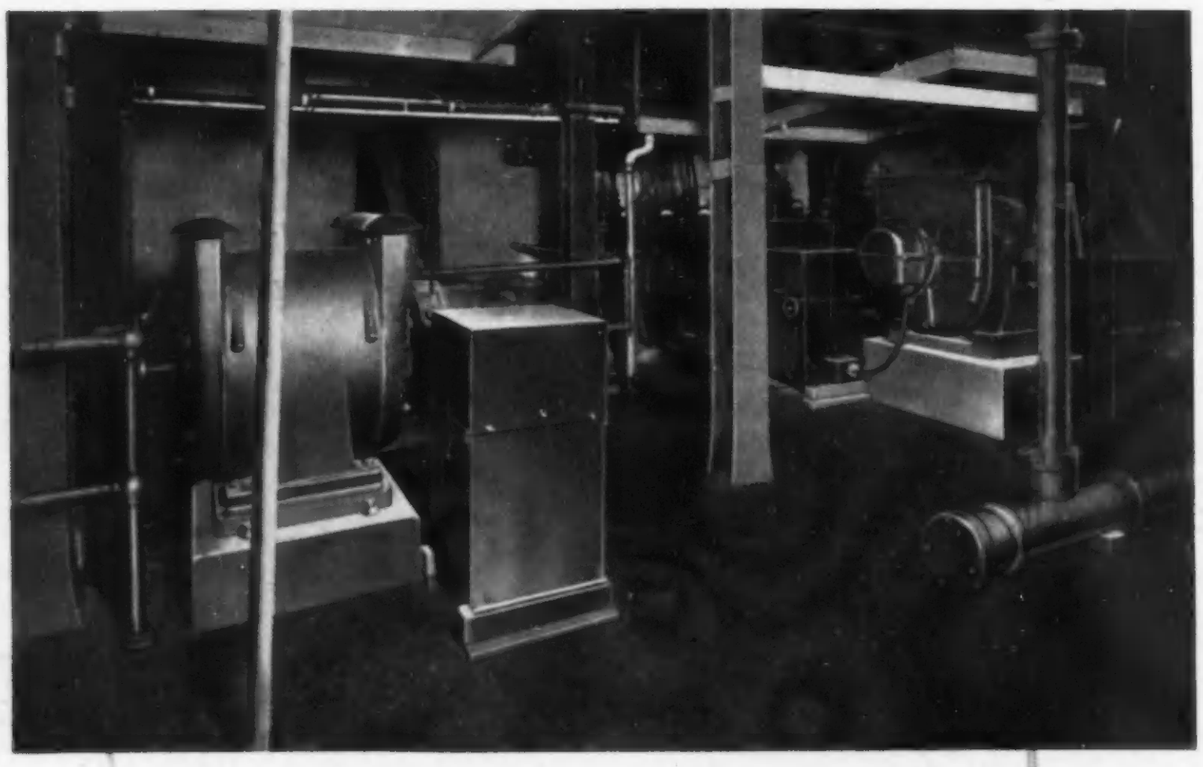

Fig. 17.—Two 75 h.p. motors in the basement driving beater and breaker groups.

It has been found in practice that the Ward Leonard system is fully capable of providing the smooth acceleration required between the required limits.

The beaters and breakers are split up for driving purposes into groups of four and two, so that groups of beaters may be isolated as required, the groups of four being driven by 120 h.p. motors (fig. 20), and the groups of two being driven by 70 h.p. motors (fig. 17). These motors are all of the slipring drip proof type with totally enclosed sliprings, started by means of hand-operated liquid resistances electrically interlocked with stator controlling oil switches of the industrial drawout pedestal type and provided with remote stop buttons for emergency requirements.

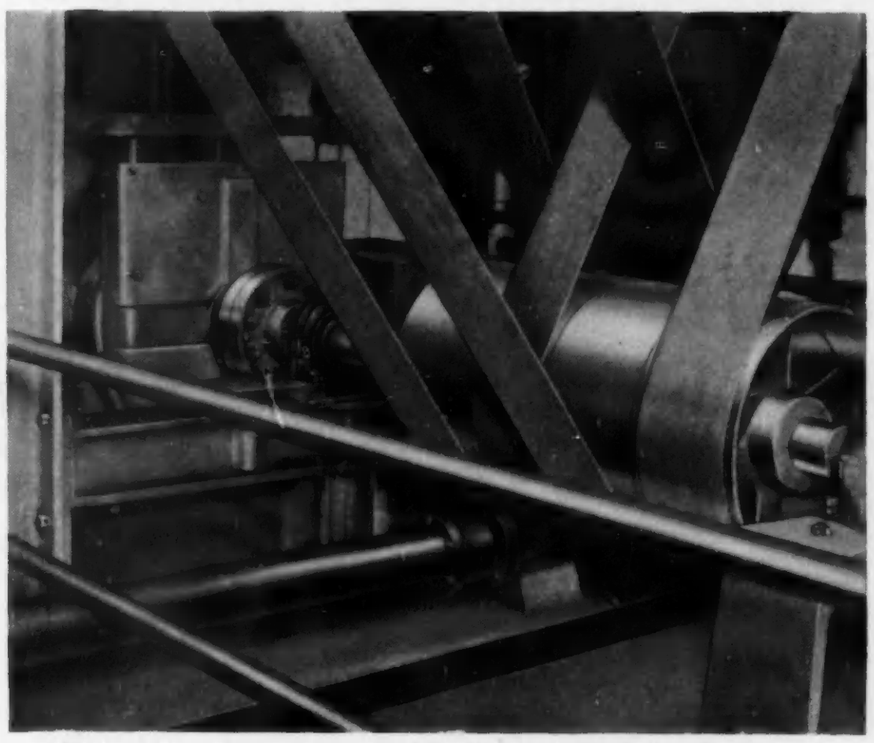

Fig. 18.—Arrangement of belt driving of beaters and breakers from motors in the basement, of which a view is shown in fig. 17.

The mechanical arrangement of the drive is shown in fig. 18 and consists of a short length of shaft supported in roller bearings carrying four pulleys driving upwards at an angle of about 45 degrees through the beater floor on to the beaters or breakers, the whole being direct coupled by means of a flexible coupling to the motor which runs at a speed of 365 r.p.m. The pulleys on the driving shaft are 27 inches in diameter driving on to 4 ft. pulleys on the beaters or breakers giving a very good ratio and an easy drive for the belts. The motor shown in fig. 20 is a synchronous induction type, rated at 120 h.p., and is capable of running at a power factor of .4 leading. It is installed for the purpose of improving the power factor of the system which is between 0.8 and 0.85. Kollergangs are belt driven by 25 h.p. slipring motors (fig. 7) mounted on wall platforms, each with a liquid starter on the same platform. The stator control is effected by an oil circuit breaker switch interlocked with the liquid starter. The motors are capable of starting up against 2½ times full load torque, a feature which is essential in kollergang drive, owing to the heavy torque necessary to overcome the inertia in the rollers. The liquid starters are capable of repeated starts and stops for inching the rollers round when emptying the pans.

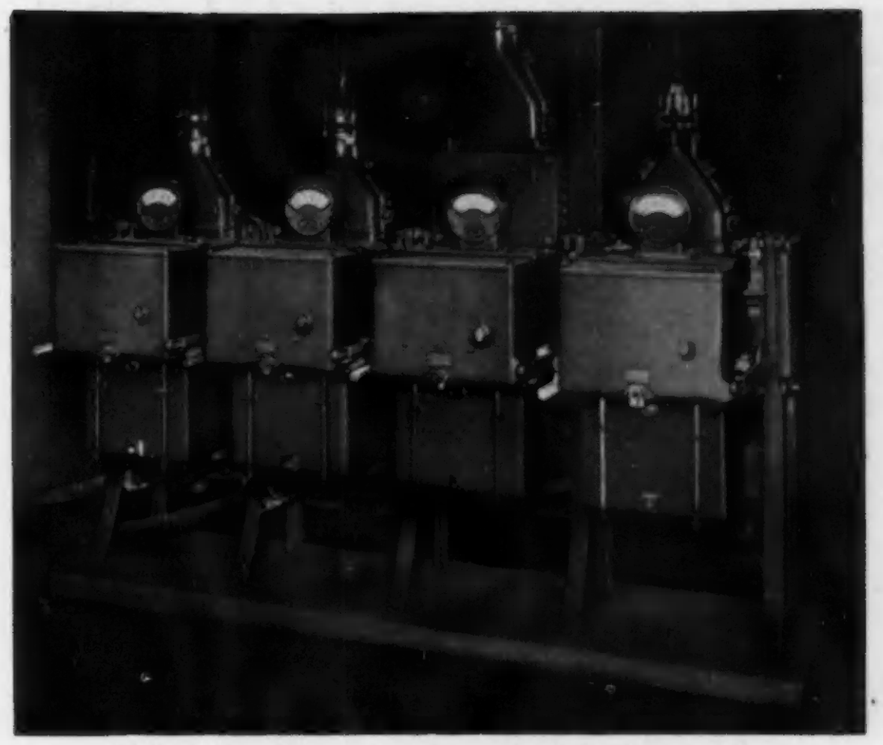

Fig. 19.—One of the pedestal draw-out switchboards for controlling beater and breaker motor circuits.

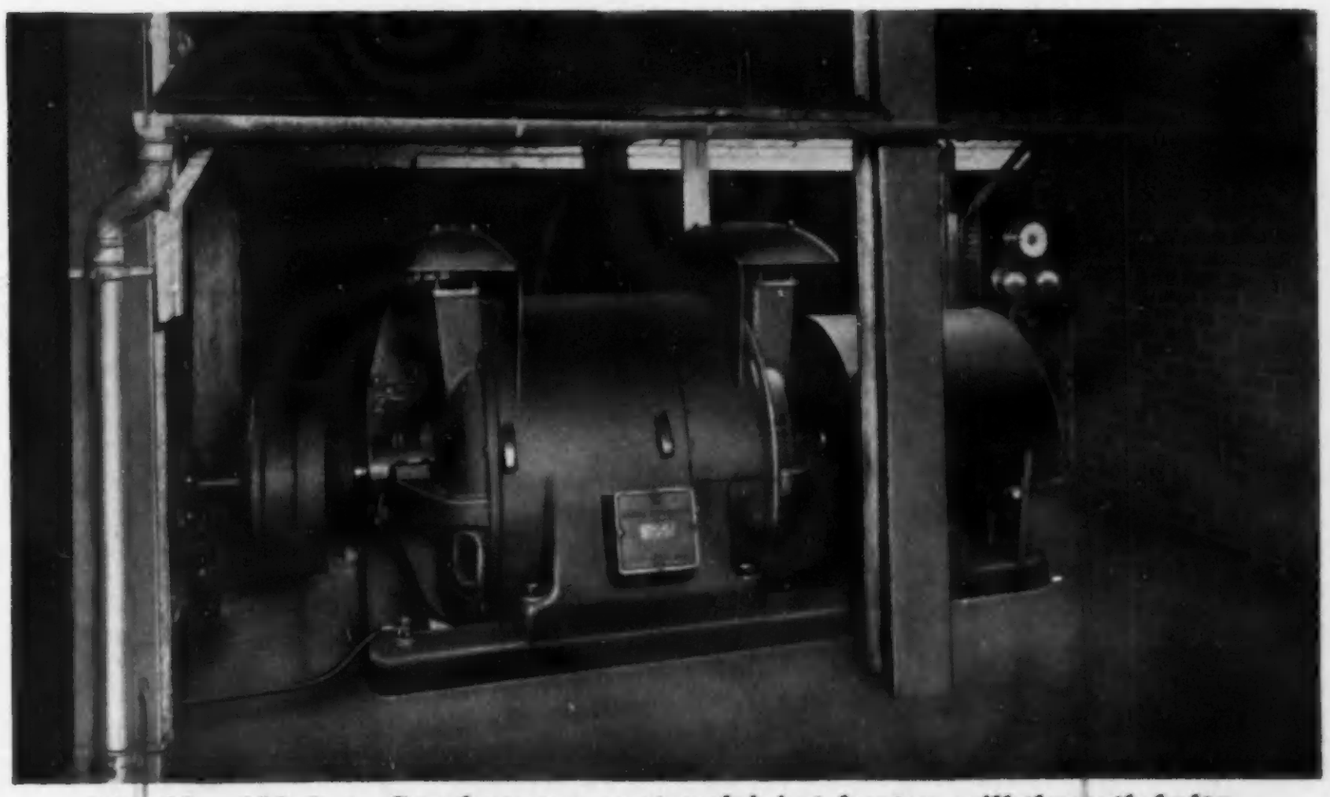

Fig. 20.—120 h.p. Synchronous motor driving beater mill through belts. This motor is used for improvement of power factor.

It should be stated in conclusion that since the starting up of the new power plant, valuable economies have been effected in working costs. A further point of interest is that paper was actually being made within an hour or two of the starting up of the plant.

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G3599

Load Ratio Control for Transformers.

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WITH the introduction of the "Grid" or "ring main" system of electrical distribution, involving the operation of distantly separated stations in parallel, and the feeding of bulk supplies over long lengths of line, supply engineers have to make provision for widely varying conditions as regards voltage drop along the line.

One method of obtaining voltage control is to install transformers with adjustable tappings at various points *en route*. Such tappings are fitted almost as a standard feature on transformers and the methods of tap changing can be classified into three groups :

1. Tappings brought to a terminal board, or the equivalent, just under oil level. This is the cheapest method and is satisfactory if the correct tapping can be selected once and for all before the transformer is erected on site and connected to the system. It is necessary with this construction to remove the lid of the transformer to make any adjustment to the tappings, and obviously its use is restricted to the "free oil level" type of transformer, and should not be used in conjunction with transformers that are fitted with conservators, or those for outdoor use.
2. Tappings brought to an "off-load" tapping switch which is mounted on the framework of the transformer inside the tank below oil level. Before operating the tapping switch the supply must be disconnected from both H.V. and L.V. sides, but the tapping adjustment may then be carried out without removing any oil or any part of the cover.

   Sufficient attention has not been paid to the necessity for robustness in this type of switch, and it is very desirable that in the case of three phase transformers, all three switches (one per phase) are operated at the same time by the same operating handle. The laminated type of brush contact should not be used in this type of switch.
3. Tappings brought out to an "on-load" tapping switch. Here the adjustment to the tappings, *i.e.*, the voltage ratio, is carried out without disconnecting the transformer from the supply and without interrupting the circuit. The actual tap change can be effected by (*a*) hand operation (*b*) remote control by push button (*c*) completely automatic control.

It is the intention in the present article to describe the more usual methods of accomplishing on-load tap changing. In passing it should be mentioned that methods (1) and (2) are comparatively cheap to install, whereas method (3) is costly.

Transformer manufacturers usually make two or three types of "on-load" switches, the cost of which depends on the voltage and kVA to be controlled, and it should be remembered that the cost of providing on-load ratio control cannot be expressed as a constant percentage of the cost over a range of transformers. The cost is an approximately constant figure for any particular type, and therefore, as a percentage of the total transformer price, it increases considerably as the output of the transformer falls.

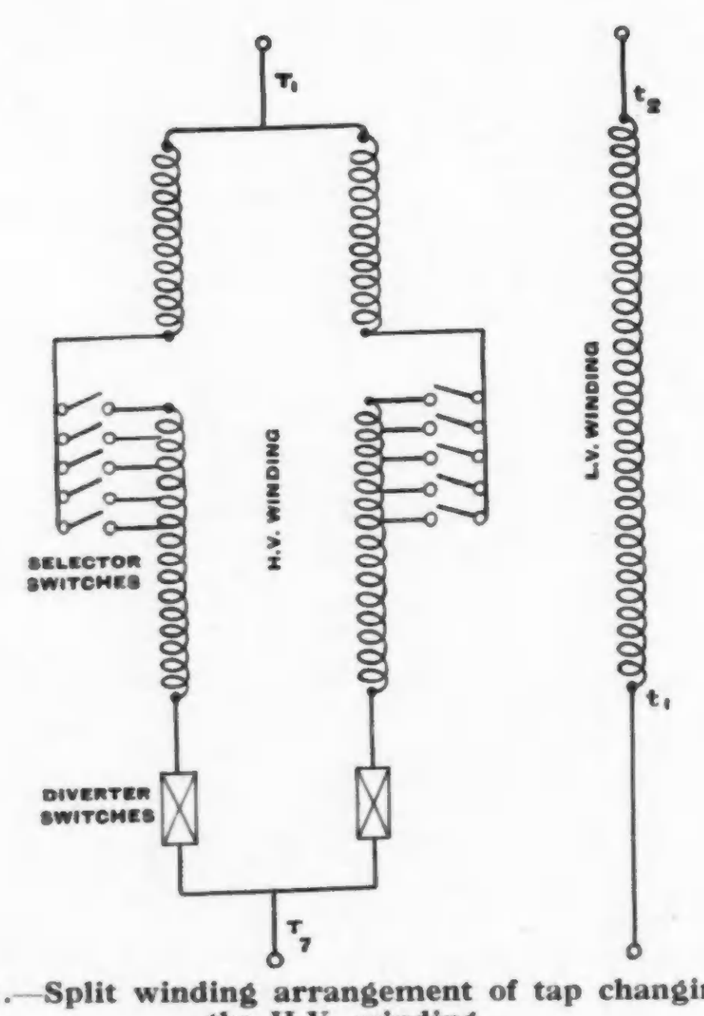


Fig. 1.—Split winding arrangement of tap changing on the H.V. winding.

METHODS OF ON-LOAD TAP CHANGING.

Broadly, on-load tap changing on transformers can be effected by the following three methods :

(*a*) By tap changing on the actual transformer, the tappings being brought out on the H.V. winding of the transformer.

(*b*) By tap changing on actual taps brought out on the L.V. winding of the transformer.

(*c*) By tap changing in a subsidiary booster circuit.

Method (*a*) is usually understood in modern practice when reference is made to load ratio control.

Method (*b*) is useful on occasion and frequently offers an economical solution to the problem of catering for voltage regulation in the case of the smaller transformers. For small units a very useful form of this type is the neutral point regulator, in which a three arm faceplate type regulating switch is connected in the neutral point.

Method (*c*) is especially useful when regulation is required on an existing main where step-up and step-down transformers are installed without any provision for tap changing on load. This method also offers a simple means of phase angle control which will be described later. A further advantage is that the actual tap changing switch, being in a subsidiary circuit isolated from the main line, can be designed for a suitable balance between the operating voltage and current.

METHOD (a)—TAP CHANGING ON THE H.V. WINDINGS OF THE TRANSFORMER.

Under (*a*) various schemes are in use but they can conveniently be grouped in three divisions:

(1). Split winding arrangement.
(2). Induction regulator arrangement.
(3). "Preventive auto" arrangement. This is sub-divided again into two, dependent on the method of utilisation of the preventive auto or choker.

SPLIT WINDING.

The split winding arrangement is shown in fig. 1 where it will be seen that the primary winding of the transformer is divided into two separate halves, identical tappings being brought out on each half winding.

There are, however, many objections to the use of this system, though it is successfully in use.

Each half winding must be designed momentarily to carry the full load current when a tap change is being made. The reactances between the various windings have to be arranged carefully so that the reactance of each half winding, in respect to the winding t_1 t_2, is the same as the reactance of the two half windings when connected in parallel to the winding t_1 t_2. Moreover, owing to the difficulties of winding mechanically strong coils, due to the fact that the total copper section is halved as regards any particular coil, this method cannot generally be used by itself. Finally, four times the number of taps have to be brought out per phase or leg than is the case with the preventive auto method described later.

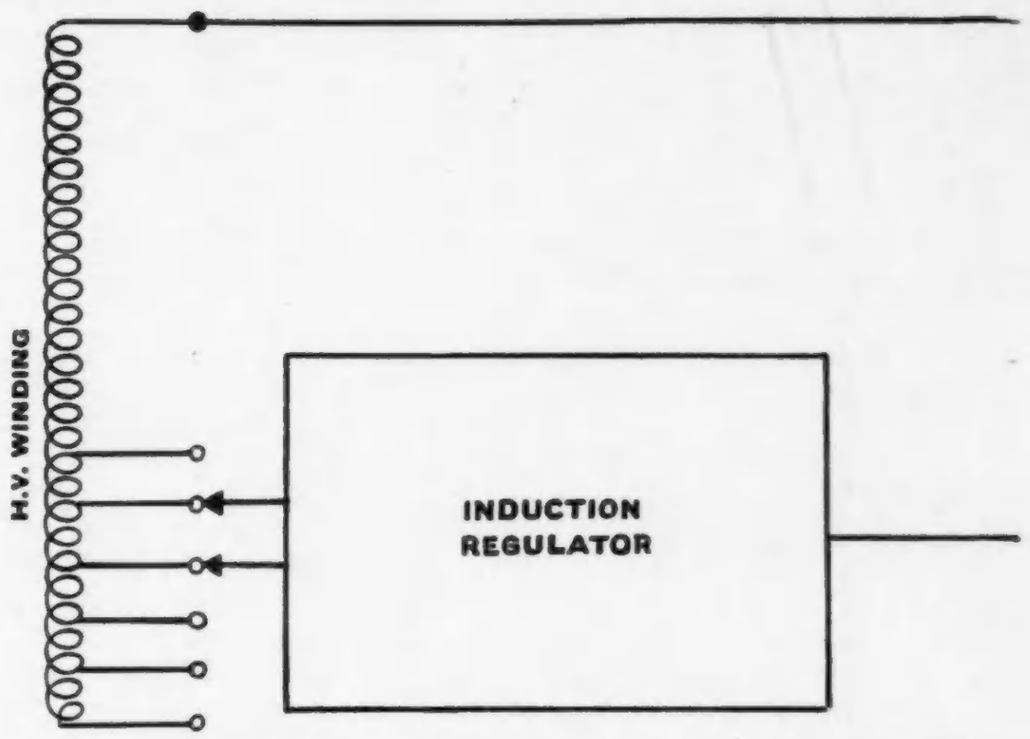


Fig. 2.—Induction regulator arrangement of tap changing.

INDUCTION REGULATOR.

An induction regulator arrangement is shown in fig. 2.

Although the induction regulator enables a smooth variation of voltage to be made between steps, there exist certain inherent disadvantages which militate against the general use of either of the types shown. The cost is high, the difficulties of insulating between turns to avoid break-down caused by surges (a very real source of trouble) and under certain conditions a considerable increase in losses, all tend to relegate this method into the "special" class; as such, it is not universally applicable, and is consequently not described in detail in this article.

It may be of interest at this point to mention the "sliding core regulating transformer." Although this has not been employed for tapping adjustment, it has been used very successfully for ratio control on testing transformers. Briefly, the secondary winding

is wound on a fixed core and the primary winding, which is in two halves, is wound on moveable yokes which slide over, and are in intimate contact with, the core. Theoretically, it is generally similar to an induction regulator, but differs in that the yokes slide over the core in a horizontal plane, as compared with the rotating motion in the induction regulator.

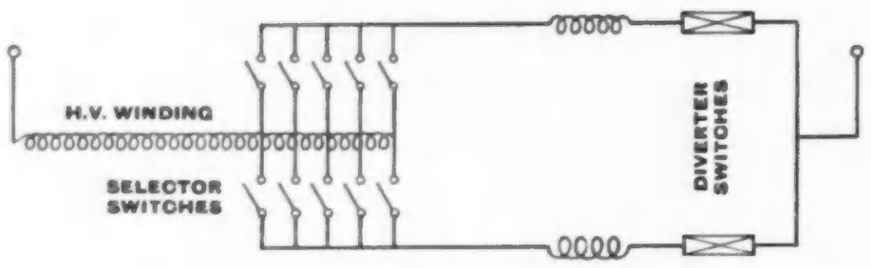


Fig. 3.—Series reactor arrangement.

PREVENTIVE AUTO.

The preventive auto arrangement is most generally used in this country, on the Continent, and in America, but here again three schemes, each employing a preventive auto, or reactor, are in use ; the diagrams for these are shown in figs. 3, 4 and 5.

In fig. 3, it will be noticed that one tap and two terminals are required per step, and the reactors are used during the period of the tap change to control the circulating current. (NOTE.—This is catered for in the split winding method by the inherent reactance in the two half windings).

In fig. 4 the preventive auto has to be designed to meet two separate operating conditions. Firstly, when switch 1 is closed, the load current passes through one half only of the auto which thus acts as a reactor ; under this condition it introduces into the circuit a small out of phase voltage vector the effect of which increases as the load power factor decreases. Secondly, when switch 2 is closed, the auto bridges a tapping section in the main transformer and therefore acts as a simple auto transformer, the mid point "lead away" giving the equivalent of a tapping in the transformer mid way between taps 1 and 2.

This arrangement suffers from the special design of preventive auto required, and from the fact that on alternate steps the auto acts as a reactor, and thus equal voltage steps are not obtained.

In figs. 5 (a) and (b) are shown the most generally used arrangements. The two diagrams are grouped together because in effect they are similar, except that in 5 (a) a separate short circuiting switch is used across the preventive auto, whereas in 5 (b) the same electrical effect is obtained by means of the brushes or contacts of the selector switch which are connected together at alternate steps on the same contact, thus shorting the "preventive auto" on the contact. Arrangement 5 (b) is thus preferable, as it avoids the use of a third operating switch with its attendant mechanical complications.

In order to enable the tap change to be made in methods (*a*) 1 and (*a*) 3, without interrupting the supply, two parallel paths are provided in each of which a switch is fitted which is capable of breaking half the load current at the moment of tap change.

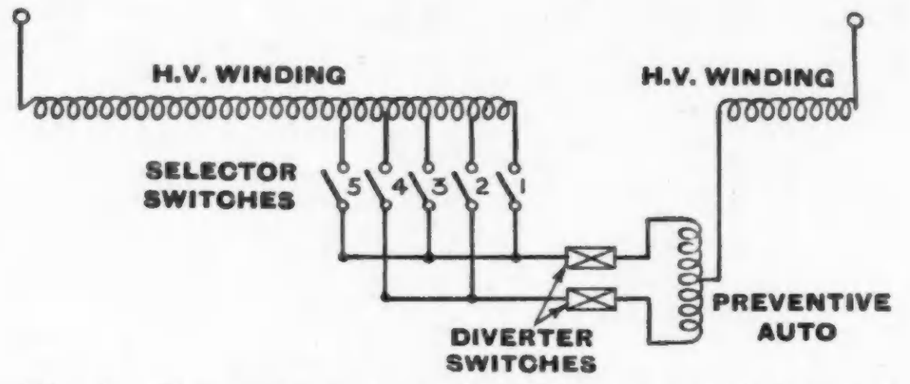


Fig. 4.—Preventive auto without short circuiting switch.

These are usually termed "diverter switches," one or other of which is opened when tap changing in order to remove load from the "selector" switch which selects the new required tapping. The operation of the diverter switches in conjunction with the selector switch is shown in fig. 6.

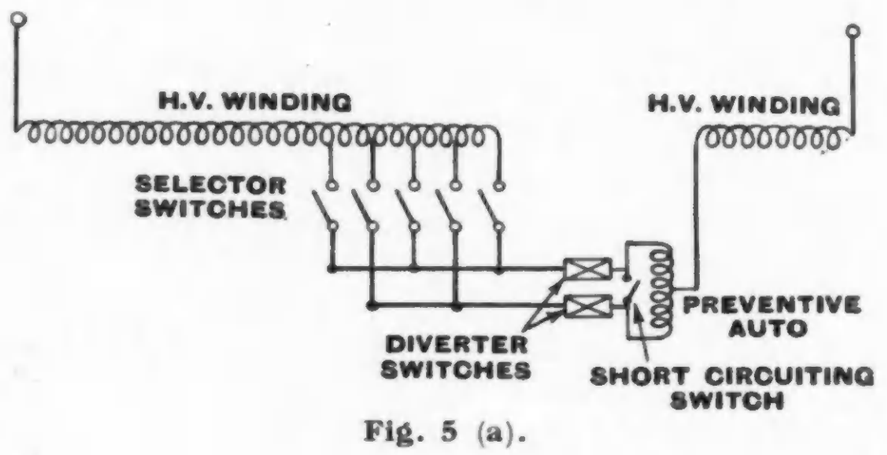


Fig. 5 (a).

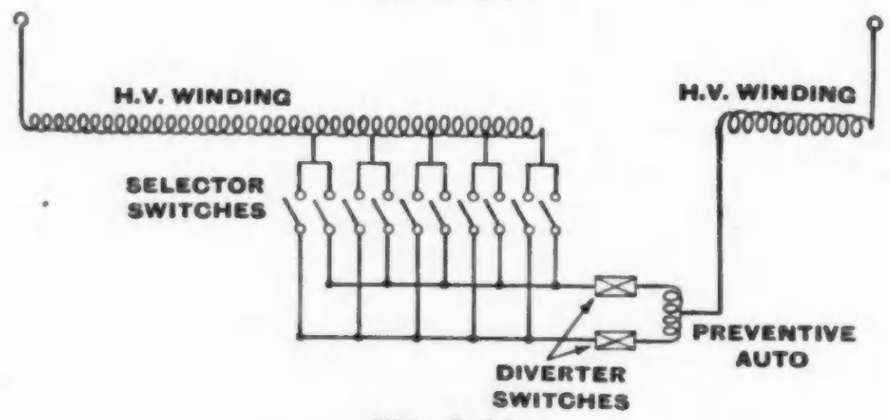


Fig. 5 (b).

Figs. 5 (a) and (b).—Preventive auto with short circuiting switch.

METHOD (b)—TAP CHANGING ON THE L.V. WINDING.

Method (*b*) can be used advantageously in certain cases where tappings on the L.V. side offer the correct solution to the particular problem. It is however not general practice and it is seldom possible, because of the value of the volts per turn of the design, to bring out tappings on the L.V. side of a transformer at correct intervals to give the required voltage ratio adjustment. For example,

with a transformer having 18 secondary turns, a $2\frac{1}{2}$ per cent voltage variation would necessitate a tapping at 0.45 turns, while a 5 per cent voltage variation requires 0.8 turn, which obviously is outside practical compliance.

Fig. 7 shows in diagrammatic form the simplest form of booster arrangement for voltage control. Obviously the main double winding transformer can be replaced in special circumstances by an auto wound transformer. It is interesting to note that the

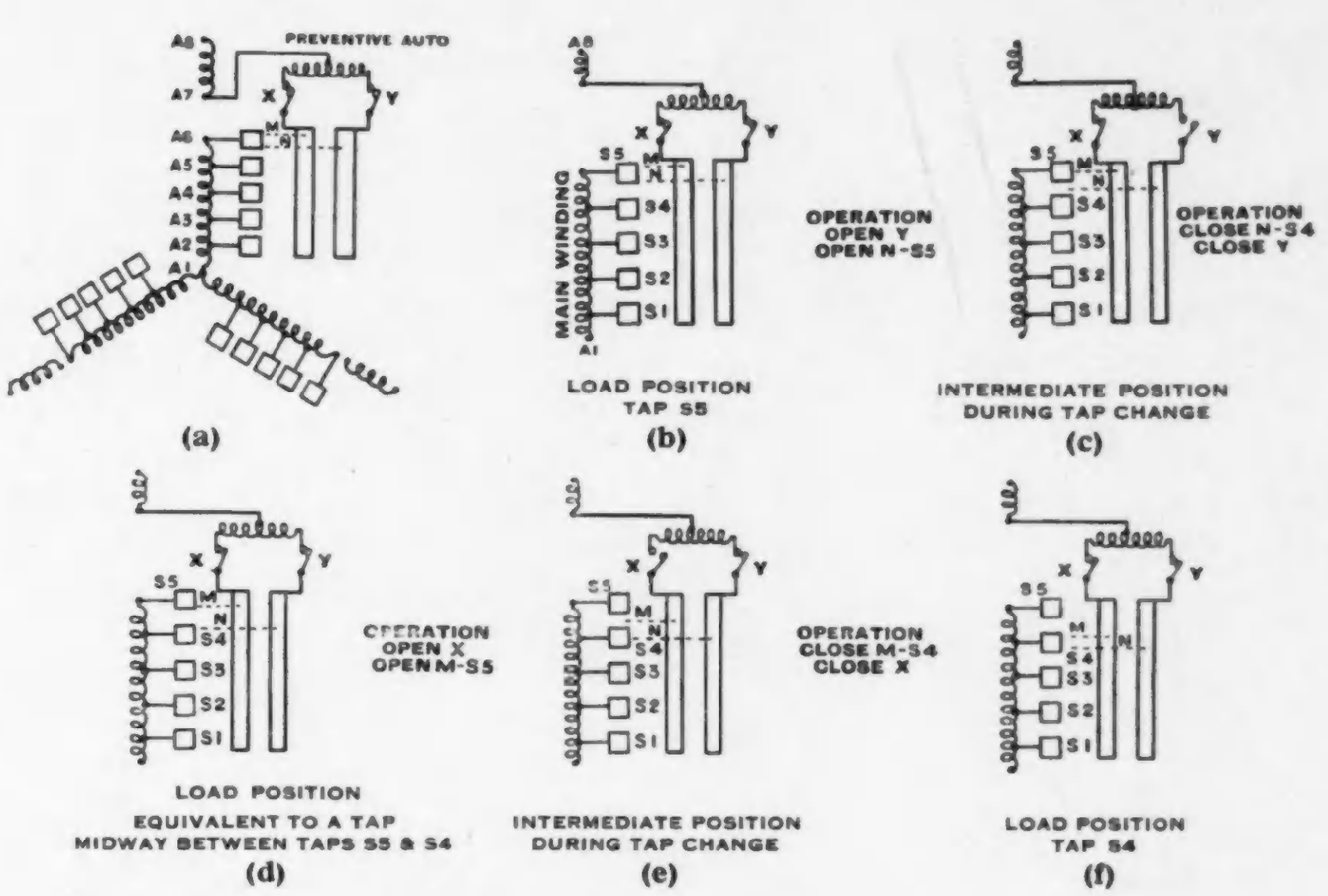


Fig. 6.—Diagram showing operation of the diverter switches in conjunction with the selector switch.

METHOD (c)—TAP CHANGING IN A SUBSIDIARY BOOSTER CIRCUIT.

Method (*c*) in which voltage variation is obtained by a separate booster offers a wide field of employment; it is possibly the most flexible arrangement

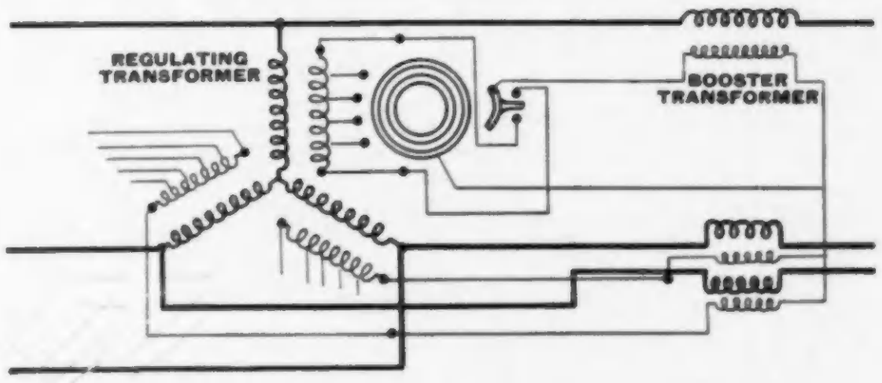


Fig. 7.—Simple form of booster arrangement.

available, but unfortunately it is very much more costly in application, and the equipment occupies considerably more floor space than the equivalent in load ratio control on the actual transformer unit.

Where, however, ratio control has to be introduced into an existing distribution scheme whether for voltage, power factor or phase angle control, this method is the best and frequently the only method generally applicable.

inherent phase angle shift with this arrangement is negligible, being a matter of minutes only. It will be seen that any suitable values for the voltage and current in the subsidiary switch circuit may be used, so long as the total power in that circuit meets the required condition of boost.

A modification of the arrangement is shown in fig. 8 where a "fixed" boost is included. In certain cases a considerable reduction in the "frame" kVA, and therefore cost, can be effected by a judicious use of "fixed" and "reversible" boosts.

In fig. 9 a method of "line compensation" for resistance and reactance drop is shown, both the resistance and reactance drops in the line being "matched" in the regulating apparatus by suitable resistances. Another valuable feature of this method is its suitability for introducing, or rather correcting, phase angle shift by means of a rearrangement of the windings. Taking a simple case, it is apparent that if a feeder which includes a step-up and a step-down transformer is required to work in parallel with a feeder which has no transformers connected, a difference in phase angle will result at the far end, which phase angle may be of such dimensions as to preclude the paralleling of the two feeders at the

far end, except at the risk of large current rushes at the moment of switching in. To obviate such a trouble it is necessary to introduce a correcting

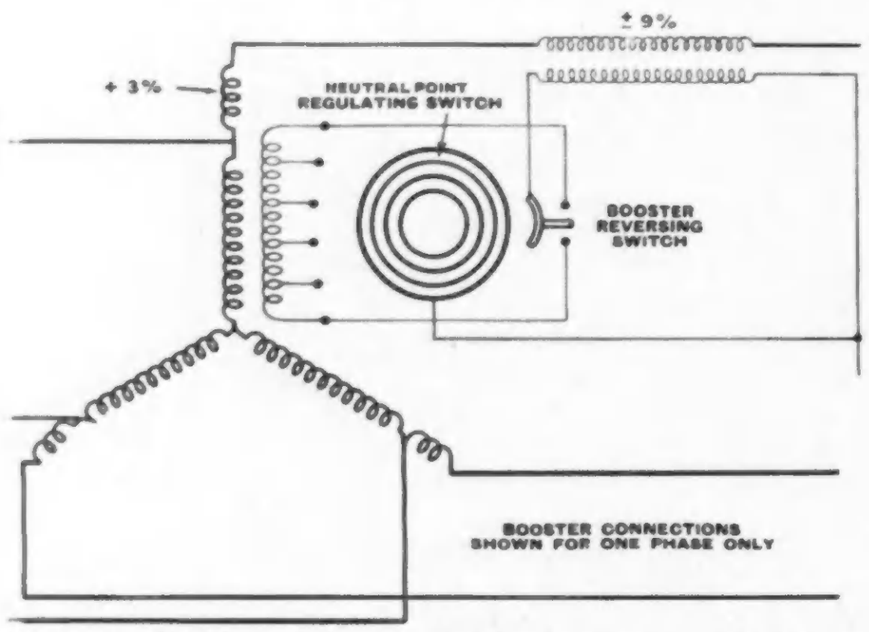


Fig. 8.—Modification of simple booster arrangement, introducing a fixed boost.

phase angle shift in one or other of the circuits, and this can easily and accurately be accomplished by means of separate booster control.

In fig. 10 are shown the vector diagrams for the straight voltage boost arrangement, while fig. 11 illustrates the basic idea of the vector arrangement for the introduction of phase shift correction; briefly, by a suitable combination of star and delta connections, a vector at right angles to the supply vector is introduced, and depending on the value of the voltage vector introduced at right angles to the main vector, the phase angle shift can be regulated to a large extent.

The method of calculating the required percentage of the main voltage, necessary to be introduced at 90 degrees is shown in fig. 12; it is based on the following formula:

E_S (phase shift voltage) = E_A (Leg voltage of system) × tan ϕ, where ϕ = degrees of shift required; from this it is seen that for every 1 degree phase shift required it is necessary to introduce a phase shift voltage at right angles equal to 1.75 per cent. of the phase leg voltage of the system.

The equipment represented in figs. 10 and 11 can be combined in one apparatus so that the voltage and also the phase angle can be controlled, but this combination would somewhat complicate the design of the main and subsidiary transformers.

CONSTRUCTION OF LOAD RATIO CONTROL GEAR.

Following this brief discussion on the various methods of load ratio control, it will be of interest briefly to describe the apparatus developed by The General Electric Co., Ltd., for this purpose.

Two sizes have been developed, Type F for small units from 750 kVA to 7,500 kVA at 11 kV, and Type G for larger units up to 75,000 kVA at 132 kV.

TYPE G TAPPING SWITCH.

Type G is shown complete with its main transformer (of 30,000 kVA output) in fig. 13; it will be seen that all the switchgear and its control are fitted externally to the transformer; while this form of construction may be slightly more expensive and takes up a little more floor space, it is undoubtedly

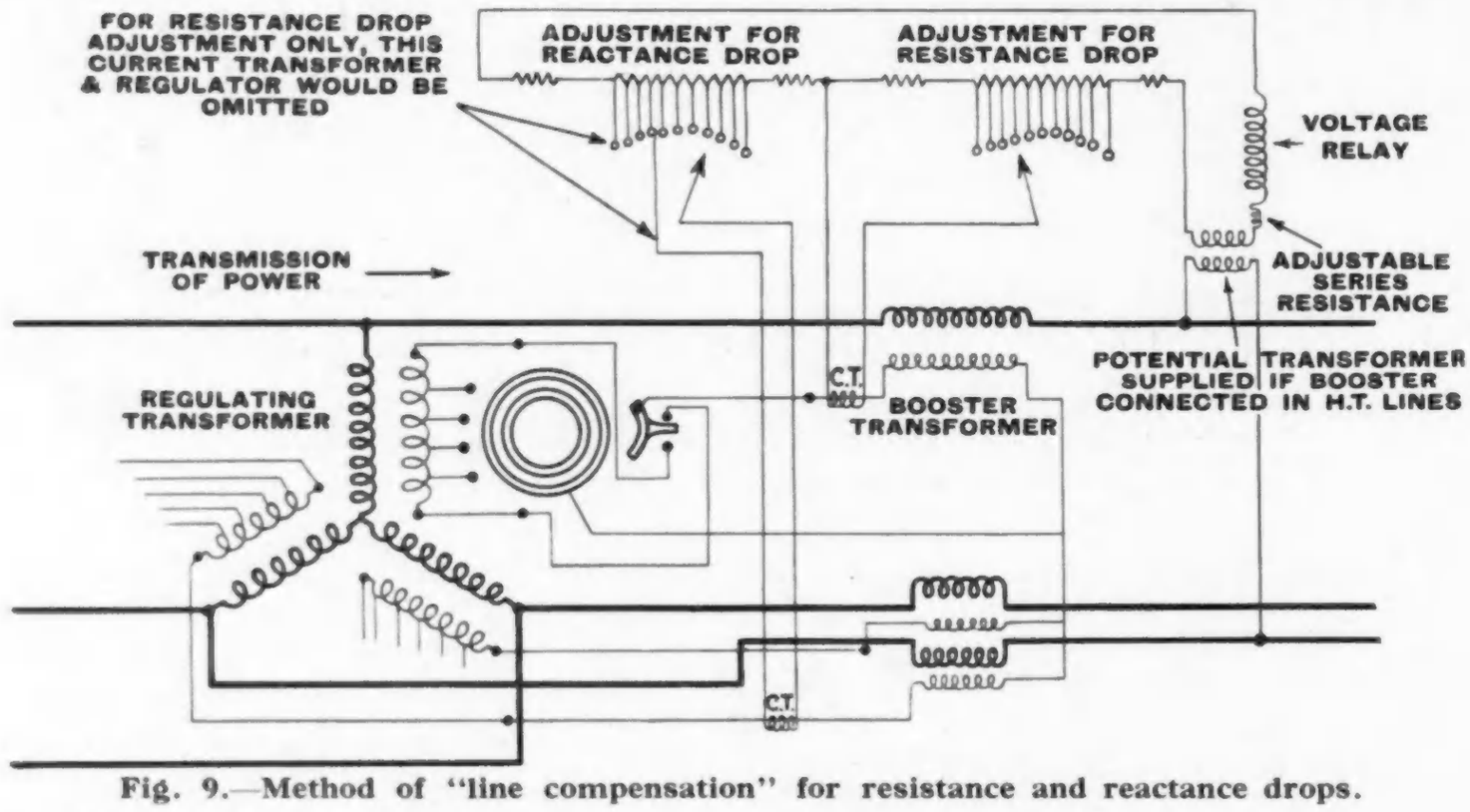

FOR RESISTANCE DROP ADJUSTMENT ONLY, THIS CURRENT TRANSFORMER & REGULATOR WOULD BE OMITTED
ADJUSTMENT FOR REACTANCE DROP
ADJUSTMENT FOR RESISTANCE DROP
VOLTAGE RELAY
TRANSMISSION OF POWER
ADJUSTABLE SERIES RESISTANCE
POTENTIAL TRANSFORMER SUPPLIED IF BOOSTER CONNECTED IN H.T. LINES
REGULATING TRANSFORMER
C.T.
BOOSTER TRANSFORMER
C.T.

Fig. 9.—Method of "line compensation" for resistance and reactance drops.

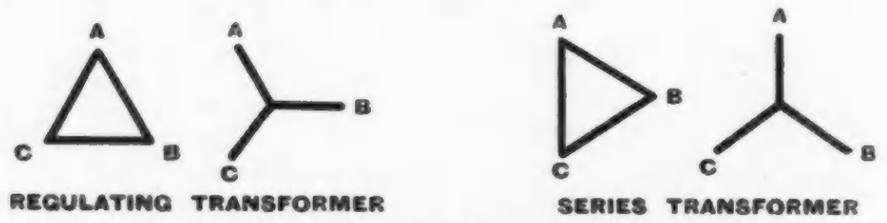


Fig. 10.—Vector diagrams for the straight boost arrangement.

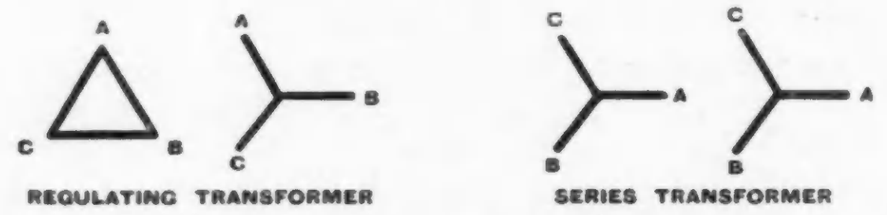


Fig. 11.—Vector arrangement for the introduction of phase shift correction.

the soundest engineering practice. All operating mechanism is enclosed and impervious to the action of the weather—a most valuable feature. Furthermore, the task of erection on site is greatly simplified,

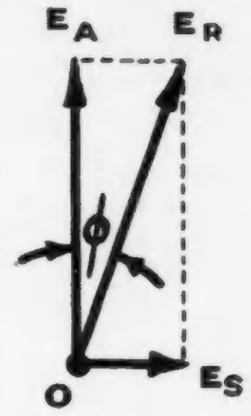


Fig. 12.—Phase shift voltage diagram.

as no temporary false cover has to be removed, and the risks attending the admission of moisture and impurities into the transformer are entirely obviated.

The three diverter switches are shown in fig. 14; these follow standard high tension oil switch practice. Figs. 15 and 16 show the control mechanism chamber and the control panel.

The diagrammatic arrangement for tap changing under load, together with the protective arrangement

Fig. 13.—Type G on-load tap changing switch coupled to 30,000 kVA "Grid" transformer.

provided, is shown in fig. 17. The sequence of operations during tap changing under load is clearly indicated on the key table. In this key a circle round the letters indicates that the switch is closed, while the absence of the circle indicates that the switch is open.

"P.A." in fig. 17 is the preventive auto which is necessary to enable the tap change to be made, and under working conditions is used in two ways; thus when switches 1A and 1B are both closed, and

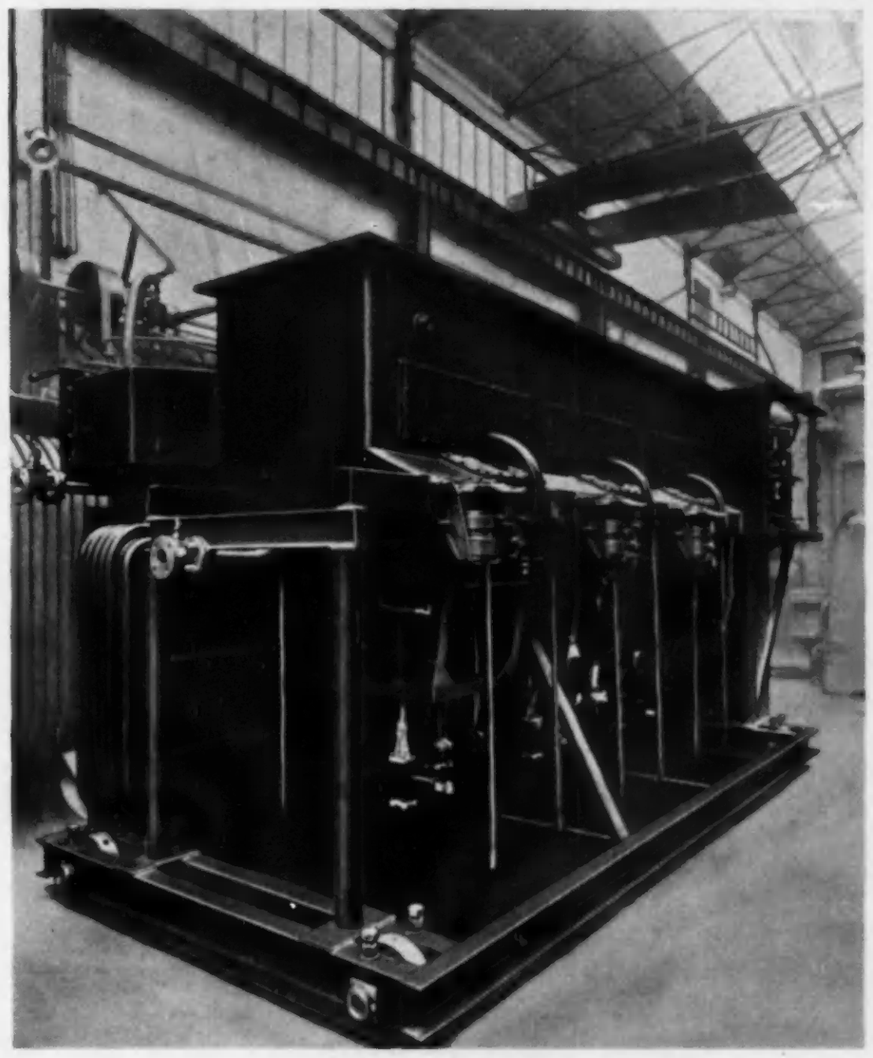


Fig. 14.—View of the three diverter switches with the tanks removed.

the highest tapping is connected, the two halves of the preventive auto are working in parallel. When switches 1B and 2A are closed the preventive auto is connected directly across the two topmost tappings, and the mid point of the preventive auto, connected to the lower half of the H.V. winding, gives the equivalent of a tapping midway between the two topmost taps brought out on the transformer. The method of protection adopted is obvious from the diagram.

It will be appreciated that in any on-load tap changing operation arrangement, there are periods during the cycle when it would be unsafe to leave the circuits as they stand for any length of time. The scheme for electrical operation has therefore been designed so that failure of the operating supply during operation will not result in the stopping of the mechanism in the middle of a tap change. Also, as far as possible it has been arranged so that if faults occur on the operating mechanism no operation of the tap changing gear takes place.

The scheme finally adopted is one in which sufficient energy to carry out a tap change is stored in a flywheel before the actual tap changing gear is permitted to begin to operate. The flywheel is accelerated to the working speed by an electric motor,

and after carrying out the change, is retarded and finally stopped by the application of a spring controlled brake. When necessary the brake is held off by a solenoid, and while the gear is actually carrying out a tap change it is also held off mechanically by a cam ; therefore in no circumstances can the brake be applied while a tap change is actually in progress.

The complete electrical cycle, from the starting of the motor which accelerates the flywheel to the stopping of the flywheel after the tap change has been completed, is controlled by a drum controller, which is geared to the flywheel in such a way that it makes one complete revolution per tap change. On this controller a number of contact segments are mounted and, as the drum revolves, these segments make contact with fingers, thus energizing the motor and other portions of the control apparatus as and when required. When the gear is at rest the drum controller must always be in the "home" position. If this is not the case, provision is made for the gear to "inch" until the home position is reached.

For descriptive purposes the complete electrical cycle can conveniently be divided into the following sections :—

(*a*) A period during which the motor accelerates the flywheel. During this period only the motor, flywheel and drum controller rotate, the actual tap changing mechanism being out of gear.

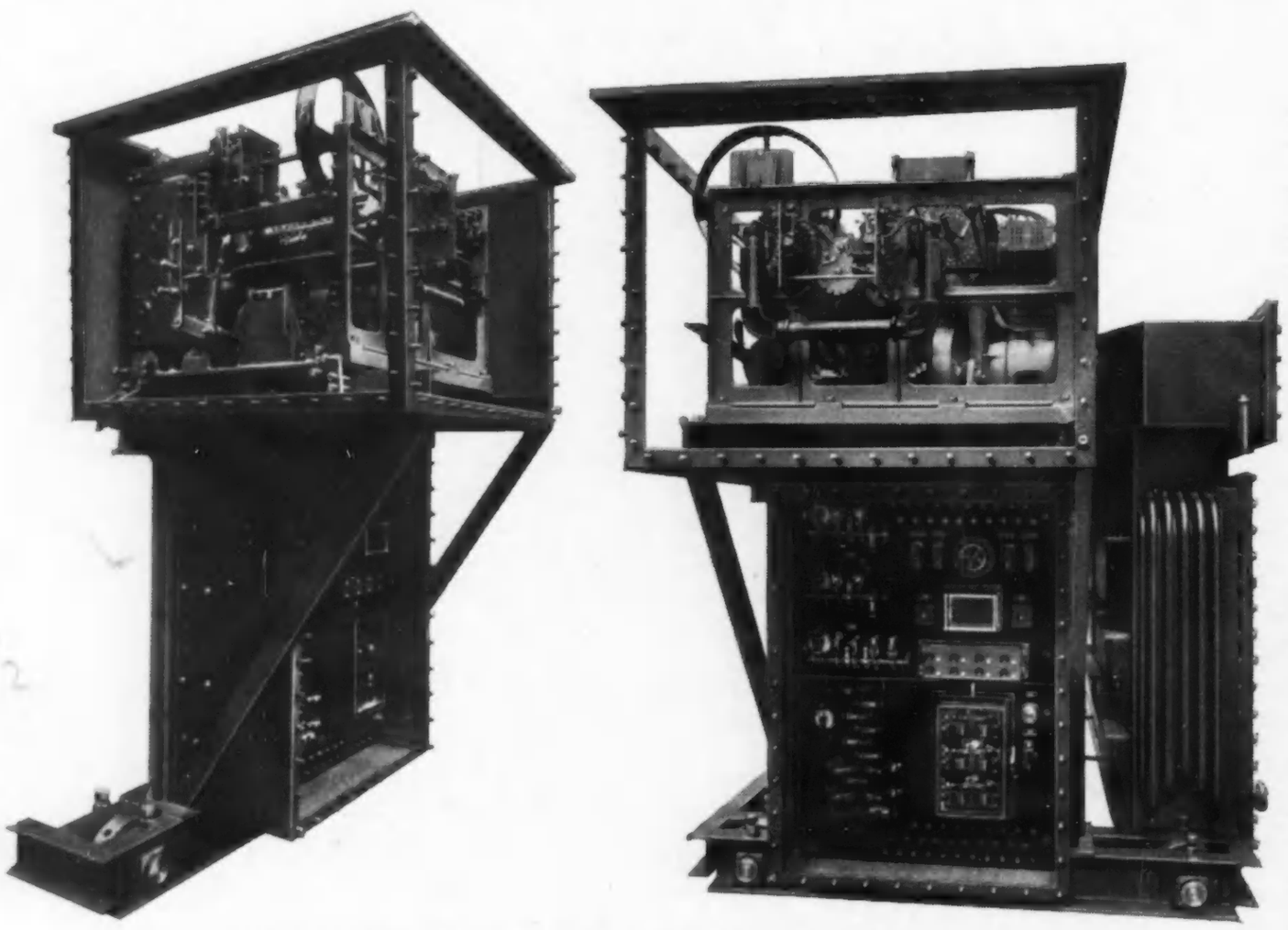
(*b*) A test period to determine whether the flywheel has reached a sufficient speed to carry out the tap change.

(*c*) An idle period with the motor switched off and the flywheel coasting. If test (*b*) fails, this period is used to apply the brake and bring the flywheel to rest before the active period begins.

(*d*) The active period, during which the flywheel becomes engaged with the tap changing mechanism, and the necessary operations are performed to change from one voltage ratio to the next.

(*e*) A period during which the flywheel is stopped and the controller "inched" to the "home" position.

The whole cycle is designed so that it is symmetrical, and is, therefore, reversible.



Figs. 15 and 16.—Views of control mechanism chamber and control panel of type G switch.

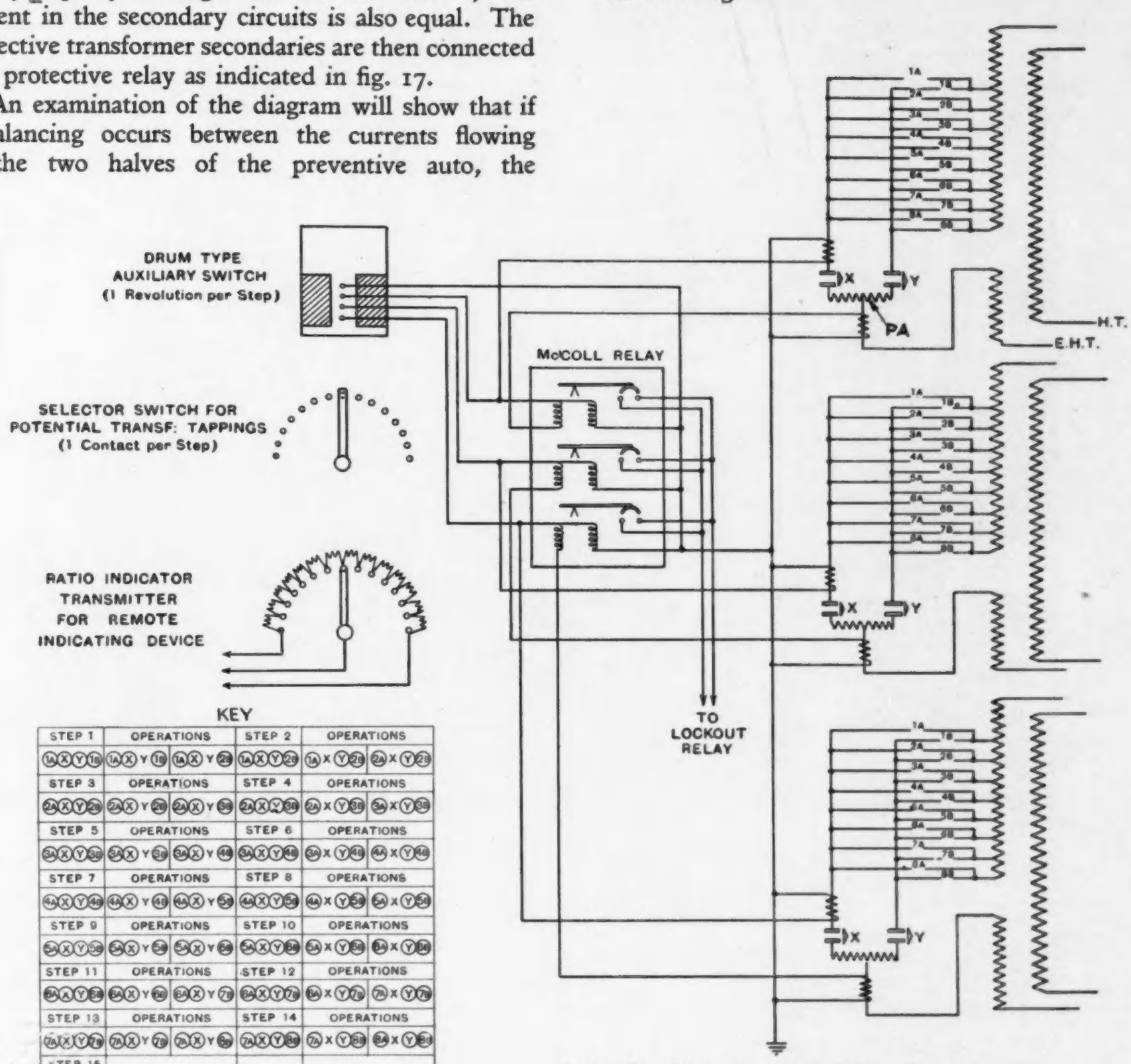
Since the electrical operation of the tap changing gear is initiated in both the "up" and "down" directions by operating one of two push buttons for a few seconds, the gear is eminently suitable for the application of remote control by either the plain pilot wire system or by supervisory gear.

In addition to giving the operator means of varying the transformer ratio, it is of course necessary to give him a clear idea of the extent to which the ratio is being varied. Each transformer is therefore provided with a ratio indicator, giving an indication at the control point of the transformer ratio in use for the time being. An alarm lamp is also provided which lights when a tap change is in progress. A further alarm is given if two transformers, which are operating in parallel, are operating on similar taps. This alarm is provided as a check on the ratio indicators, which work on the potentiometer principle and are therefore not entirely independent of voltage variations, at any rate when the operating voltage is very low, as may be the case when a fault is on the main system.

To accomplish these operations sixteen pilot wires are necessary to control the tap changing gear for each pair of transformers. The gear is mechanically interlocked and so constructed that operating mistakes are practically impossible. As a final precaution, however, the protective features detailed below are included.

A fault in a preventive auto (P.A., fig. 17) may result in large circulating currents in sections of the main transformer between tapping points. In order to protect against damage caused by these currents, two current transformers are fitted in each phase as shown in fig. 17. The ratio of the current transformers is such that when the main gear is working normally (*i.e.*, current is dividing approximately equally through switches X and Y) the current in the secondary circuits is also equal. The protective transformer secondaries are then connected to a protective relay as indicated in fig. 17.

An examination of the diagram will show that if unbalancing occurs between the currents flowing in the two halves of the preventive auto, the



KEY

STEP 1	OPERATIONS		STEP 2	OPERATIONS	
1A X Y 1B	1A X Y 1B	1A X Y 2B	1A X Y 2B	1A X Y 2B	2A X Y 2B
STEP 3	OPERATIONS		STEP 4	OPERATIONS	
2A X Y 2B	2A X Y 2B	2A X Y 3B	2A X Y 3B	2A X Y 3B	3A X Y 3B
STEP 5	OPERATIONS		STEP 6	OPERATIONS	
3A X Y 3B	3A X Y 3B	3A X Y 4B	3A X Y 4B	3A X Y 4B	4A X Y 4B
STEP 7	OPERATIONS		STEP 8	OPERATIONS	
4A X Y 4B	4A X Y 4B	4A X Y 5B	4A X Y 5B	4A X Y 5B	5A X Y 5B
STEP 9	OPERATIONS		STEP 10	OPERATIONS	
5A X Y 5B	5A X Y 5B	5A X Y 6B	5A X Y 6B	5A X Y 6B	6A X Y 6B
STEP 11	OPERATIONS		STEP 12	OPERATIONS	
6A X Y 6B	6A X Y 6B	6A X Y 7B	6A X Y 7B	6A X Y 7B	7A X Y 7B
STEP 13	OPERATIONS		STEP 14	OPERATIONS	
7A X Y 7B	7A X Y 7B	7A X Y 8B	7A X Y 8B	7A X Y 8B	8A X Y 8B
STEP 15					
8A X Y 8B					

Fig. 17.—Diagram illustrating sequence of operations during tap changing under load.

protective relay will operate. This relay operates the lock-out relay. When changing from one ratio to another, considerable unbalancing occurs for the short interval occupied by the change, but during this period the relay operating coils are short circuited.

A segment on the drum controller which makes contact during the active period is in series with the "slow speed" centrifugal switch on the motor gear. Thus, if the speed of the flywheel drops too much during the active period, a circuit is made which also operates the lock-out relay and prevents further operation as described above. This feature is included to ensure that all contacts in the tap changing gear are properly closed during normal running, while a set of drop indicators is provided to indicate which protective relay has caused the lock-out. All relays, except the lock-out relay, are self-resetting.

The addition of a voltage regulating relay connected in parallel with the operating push buttons is all that is necessary for the conversion of a single transformer to full automatic operation, but complications arise when there are two or more transformers which are operated in parallel at times.

In the first place provision must be made for both transformers to change from one tapping to the next sensibly together, and secondly, if a transformer, which has been standing idle, is to be

switched into service, the ratio of the incoming transformer must be made to agree with the ratio of the transformer on load before the main switch is closed.

Parallel operation of two or more units is simply attained by connecting the "test for speed of flywheel contacts" on all transformers in series. Thus, unless all flywheels are up to speed the brakes are applied and no change takes place on any unit.

To perform the function of self-levelling, a stepping switch is fitted to each unit which is provided with a contact segment corresponding to each tapping position. The corresponding studs on each unit are connected together, and if the unit on load is operating at, say, the fourth voltage ratio, the fourth stud on its stepper switch is made alive, and therefore the fourth stud on the stepper switch for each unit is made alive. The operation of the "close" push button switch for the main oil switch does not close the oil switch immediately, but the stepper switch on the incoming unit is made to revolve until it finds the live stud, at which point it is arrested. Other contacts on the stepper switch are then brought into operation and cause the tap changing mechanism on the incoming unit to operate until the main selector switch has connected the fourth voltage ratio for service; that is, its tapping agrees with the tappings of the units already on load. When this condition exists the closing circuit for the oil switch is completed, and the unit is put in parallel with those already on load.

The operating motor and all control mechanism are housed in one chamber at the end of the switchgear; the drive is transmitted through a Maltese cross, operated by a crank, and thence to the selector switches and the diverter switches by chains.

The selector switches are of the rotary blade type designed to ensure good contact, rigidity and ability to withstand the severe conditions of operation likely to be met with on such systems as the English "Grid."

TYPE F TAPPING SWITCH.

The type F switch for smaller kVA outputs is shown connected up for test in fig. 18. The following description applies particularly to this set which was supplied for completely automatic operation, but it is obvious that it is a very simple matter to convert it for hand or remote push button control.

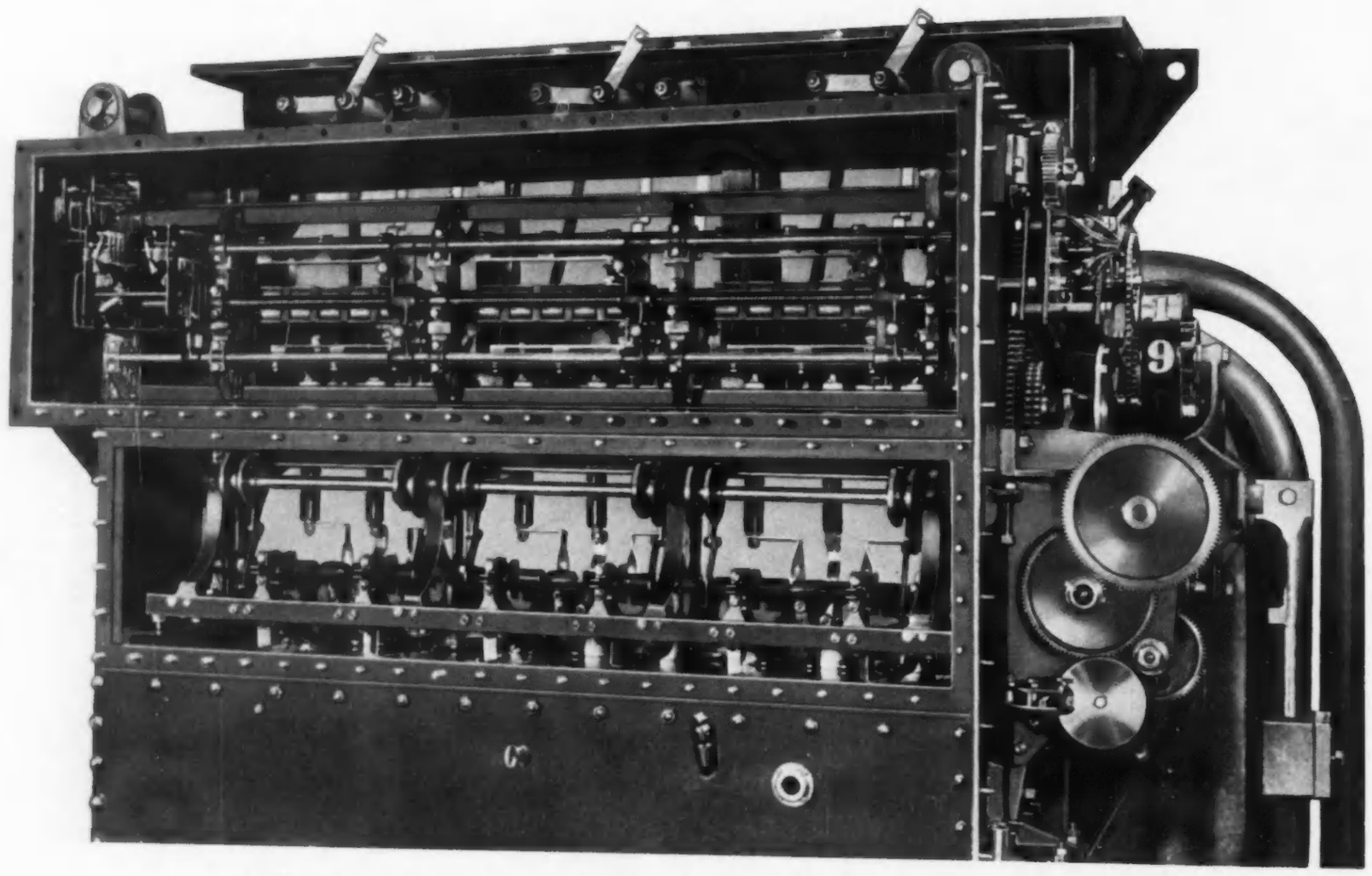


Fig. 18.—Type F on-load tap changing switch for smaller kVA outputs.

The object of the equipment is to maintain a constant voltage on one side of the main transformer, by altering the ratio of transformation with the on load tap changing gear.

The oil switches and selector switches for each phase are mechanically coupled together; only one set of control equipment is therefore required for the three phase transformer unit.

The actual tap changing is effected by potential energy stored in a weighted arm which is raised to the top position in either direction by an electric motor; the motor circuit is then broken and the weighted arm falls to the "home" position. The weight falls free from the motor mechanism and

carries out a tap change during this part of each revolution of the weighted arm.

A voltage regulating relay of the balanced beam type is provided and is energized by a potential transformer. The relay is controlled by a 110 volt solenoid and when the voltage is normal the beam floats. Should the voltage change, the relay operates in one direction or the other, and makes a contact, initiating a tap change which tends to correct the voltage.

In series with the voltage regulating relay contacts is an interlock on the main oil switch. The interlock closes when the main oil switch closes, and thus prevents the voltage regulating relay from carrying out operations unless the transformer is on load.

The contacts of a no-volt relay are also in series with the voltage regulating relay contacts to prevent the regulator initiating tap changes if the H.T. supply should fail and leave the operating supply alive.

If the voltage should vary from its normal value the voltage regulating relay, after a short time delay, will make contact and complete the circuit of the contactor for operating the tap changing motor in the appropriate direction. The motor is started up and operates through gearing to lift the weight arm to the top position where an auxiliary switch connected to the weight arm is made and so energizes a time delay relay whose contacts open circuit the "contactor for tap changing motor." The motor therefore comes to rest, but in the meantime the weighted arm has fallen over centre and completed a tap change before coming to rest again in the "home" position.

It should be mentioned that the contacts fitted in the time delay relay are normally closed but remain open for a predetermined time after the relay coil has been energized.

This time delay allows the voltage regulating relay to readjust its position after the change in voltage and thus prevents the initiating of a second tap change unless one is necessary to correct the voltage still further. Visual indication is given each time a tap change is in progress, by means of an indicating lamp mounted on the front plate of a control cubicle.

In order to give indication of the tapping at which the transformer is operating at any time, a remote indicating instrument is provided, and is actuated by a potentiometer resistance which is tapped at various points to a selector switch. This switch is driven by the mechanism in such a way that one of its contacts is made for each ratio position, thus giving certain values of resistance—one for each ratio of the main transformer.

The indicating instrument is in the nature of an ohmeter, the fixed coil being excited from the operating supply and the moving coil being energized from the tapped point of the potentiometer resistance, as previously explained. The fields produced by these two coils, cause the pointer to take up a definite position. Limit switches are also provided and these prevent the gear from over running when the limit of the tappings has been reached in either direction.

A changeover switch enables push button control to be used, in which case care must be taken to note the position of this switch when the gear is left unattended.

Mechanically, the equipment comprises the selector switches, the diverter switches and the driving mechanism. The selector switches are of the sliding contact type, moving across segments to which the transformer tappings are connected, and connecting each in turn to common busbars. The brushes which are of the finger pattern are operated by a multi-start threaded shaft which is driven through suitable gearing. The diverter switches are in this case standard contactors, each positively operated by twin-edged cams.

The operating weight mentioned above, actuates a crank which engages with a Maltese cross. This in turn drives the shafts controlling the contactor and selector switch movements, the drive being taken by a duplex roller chain. The selector and diverter switches can be clearly seen in fig. 18. The whole gear is mounted in pockets attached to the transformer tank, or in a separate chamber which is bolted to a flange on the transformer tank.

In conclusion it will be well to mention the subject of "flicker" at the moment of tap changing, as most manufacturers have probably not accorded it the attention that it deserves.

In designing the apparatus described above, using the continuously rated "preventive auto" method (designed to give a low drop during the period of tap change when the main current is momentarily traversing one half of the preventive auto winding), it was considered essential to provide a quick operation of the tap changing mechanism. It is therefore of great interest that the time of the complete tap changing operation has been cut down to under 0.4 second, which is extremely small, and is invaluable from the point of view of reduction of flicker. This speed of operation is very necessary if disturbances on the system are to be avoided.

In spite of this reduction in time of operation, ample overlap is allowed between the opening of the diverter switch and the opening of the selector switches, as it is essential that the current be definitely interrupted before the selector switch commences to move.

It is perhaps needless to emphasise the absolute necessity of "timing" all on-load switches by means of oscillograph records before any design can be passed as satisfactory.

Industrial Electric Heating.

PART III.—THE HEAT-TREATMENT OF STEEL.

By VERDON O. CUTTS,

Industrial Heating Dept. of The General Electric Co., Ltd.

Part II. *of this series* (*Vol.* II. *No.* 1) *concluded with some general references to hardening processes as applied to steel, and the use of electric furnaces for these purposes was discussed.*

In the present article the author continues this subject and describes some particularly interesting developments that have recently taken place in the case hardening of steel by processes which have been made commercially possible by the electric furnace.

ONE of the most important fields of usefulness for the electric furnace and one in which much progress and real development has recently been achieved is in connection with the hardening of steel. Even during the last two years new processes have been developed which are revolutionising works practice in this respect. Before proceeding to describe these developments, however, it would be well to review the factors governing the choice of a suitable steel and its heat treatment

Although the electric furnace is rapidly assuming a dominating position in the hardening shop, there are, of course, other important factors besides the furnace itself which must be taken into consideration. These cannot be completely ignored, even in an article of this kind, without loss of balance or perspective.

The works manager who is responsible for the production of working parts which are to be made of steel and which must possess known physical properties, has to consider the three following main factors in the order in which they are given :—

(*a*) Choice of suitable steel.

(*b*) Heat treatment required.

(*c*) The process and means of heat treatment.

All three factors are of equal importance and to a large extent interdependent.

(a)—CHOICE OF A SUITABLE STEEL.

One of the most notable evidences of the progress which has been made during recent years in the metallurgy of steel has been the production of special steels for almost every known purpose and

Fig. 1.—Typical electric cyanide hardening furnace.

duty. The very existence of such a multiplicity of steels necessitates a well informed and wise choice of steel for each individual use and purpose. This, of course, is primarily the work of the metallurgist, and in many cases the user wisely relies upon the judgment of a reputable firm of steel makers whose metallurgical knowledge is supported by the accumulated experience of the users of their steels for a wide range of purposes.

(b)—HEAT TREATMENT REQUIRED.

The specification of a heat-treatment programme that will develop and render permanent desired physical characteristics in a suitable steel is obviously a matter of vital importance if the best service is to be assured on an economic basis. As a rule this is dictated by a specialised experience or suggested by the steel maker.

(c)—THE PROCESS AND MEANS OF HEAT TREATMENT.

The third factor, that of the choice of the best process and means of carrying out the heat-treatment programme decided upon, has an important bearing on production costs and on the ultimate life of the product.

The heating of steels in electric furnaces for oil, water or air hardening is well-known and has been dealt with already. The carburising or case-hardening process is probably one of the best known methods of obtaining a hard wearing surface on steel parts. This process, as carried out in box type or continuous conveyor type electric furnaces, was briefly described in Part II. of this series. There are, however, several variants of the process which are rapidly growing in importance, some of which should now be considered.

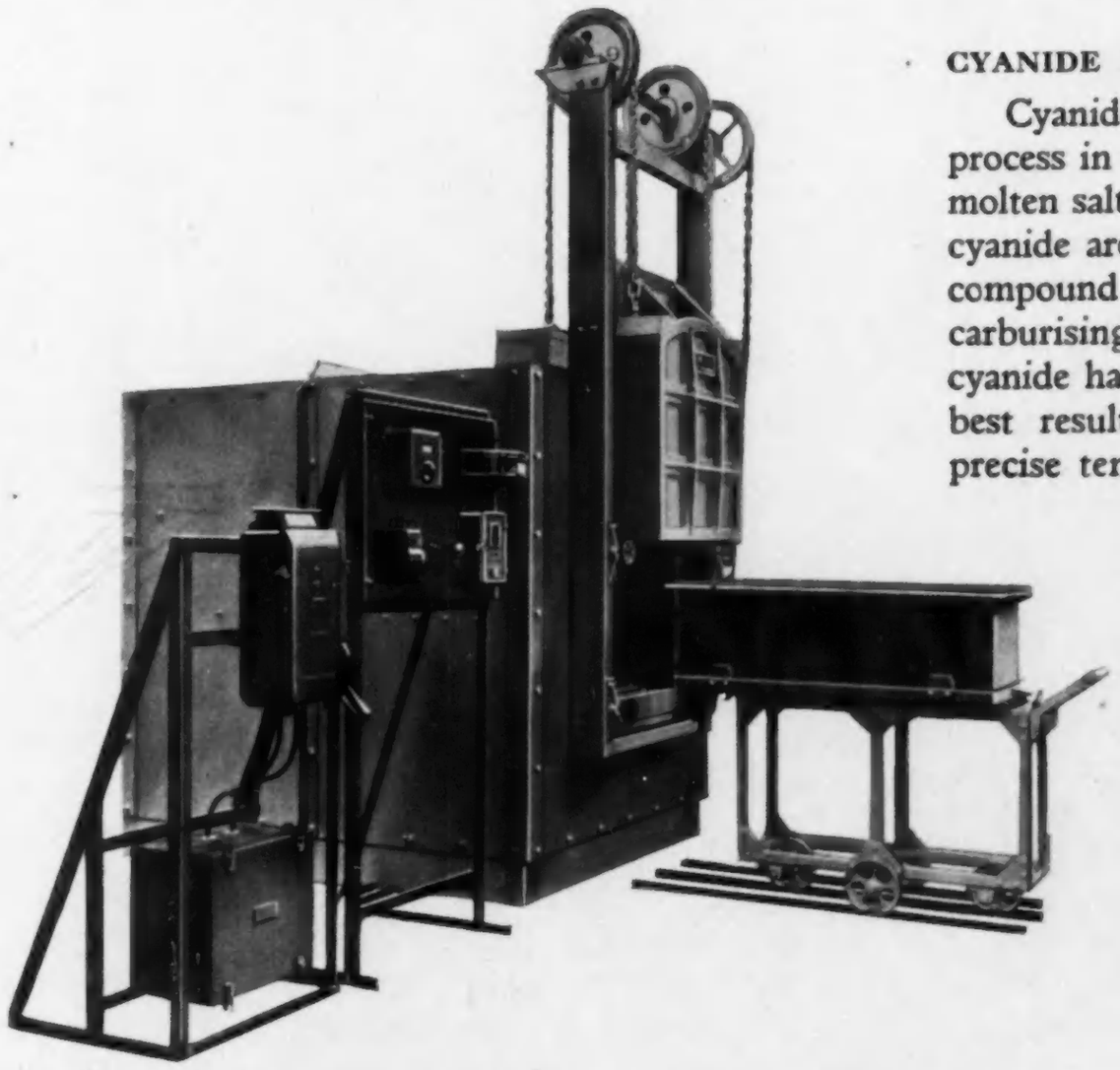


Fig. 2.—Electric nitrarding furnace with automatic temperature control panel, nitrarding box and charging truck.

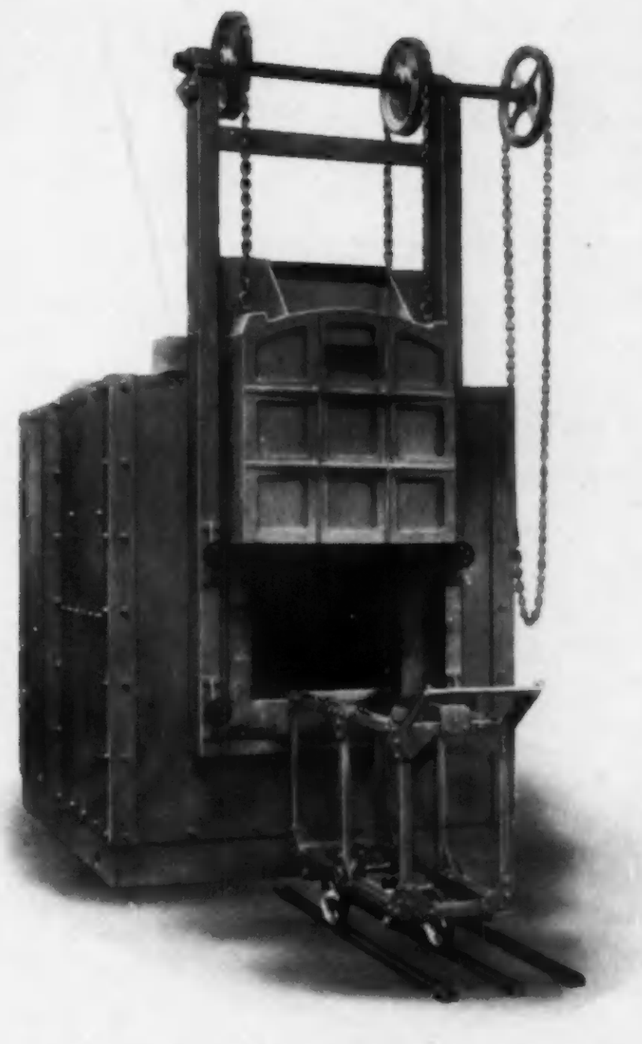


Fig. 3.—Front view of electric nitrarding furnace and charging truck.

CYANIDE HARDENING.

Cyanide hardening is a surface or case-hardening process in which steel pieces are heated in a bath of molten salts, of which sodium cyanide and potassium cyanide are typical. Cyanogen, which is a chemical compound of carbon and nitrogen, is the active carburising agent in this instance. A typical electric cyanide hardening furnace is shown in fig. 1. If the best results are to be obtained by this process, precise temperature control is essential; hence the growing demand for electrical heating for the purpose. The furnace illustrated is fitted with automatic temperature control gear, the effect of which is particularly advantageous when applied to cyanide hardening equipment.

The working temperature varies between 900 and 950 degrees Cent. If suitable steel is employed and a good brand of cyanide used in the bath, any reasonable depth of case may be obtained. With cyanide hardening there is little or no danger of that sharp line of demarcation between case and core which produces a liability to

exfoliation or peeling of the case. Whereas with the box carburising process soft spots may be caused by careless packing, the method of heating in the cyanide hardening bath ensures freedom from this danger. Moreover, distortion is reduced to a minimum.

NITRARDING.

Nitrarding is the most recent development in the hardening of steel and is, for many reasons, extremely interesting and important. It is a case

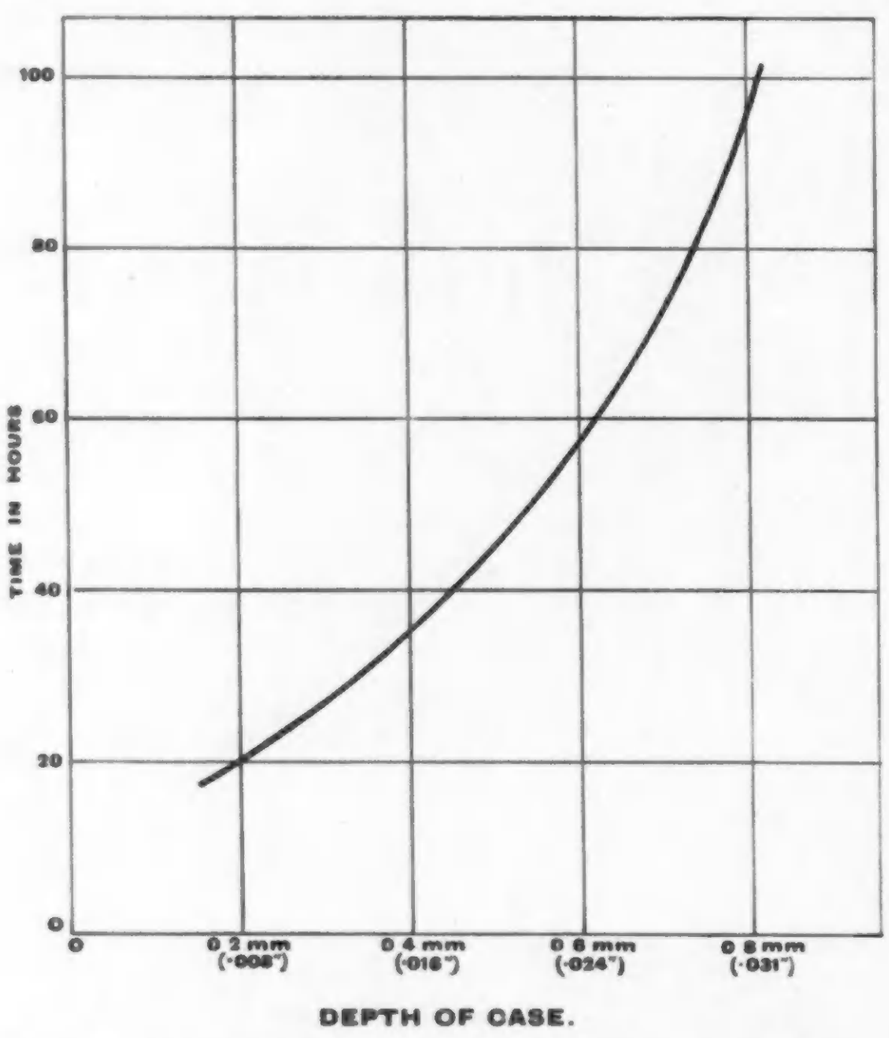


Fig. 4.—Relationship between length of time of hardening process and depth of case obtained.

hardening process which differs in certain vital respects from those previously considered. The method consists essentially of heating special alloy steels to a temperature of approximately 500 degrees Cent. (932 degrees Fahr.), and holding them at that temperature whilst exposed to the action of ammonia gas. Pieces to be hardened by the nitrarding process must be made of one of a series of special alloy steels which are known in this country as Nitralloy Steels. These steels invariably contain a small percentage of aluminium together with small percentages of chromium, molybdenum, vanadium or other element which is known to assist in the nitrarding process. The carbon content of Nitralloy steels varies, of course, according to the mechanical properties required in the core. It should be noted, however, that the carbon content of a steel, within normal limits, has no influence on the hardness of the case produced by nitrarding. The finish-machined and heat-treated pieces are placed in a gas-tight box made of a heat-resisting alloy, and fitted with inlet and outlet tubes for the circulation of ammonia gas. The box is charged into a special electric furnace and brought to the nitrarding temperature at which it is held for the length of time necessary to produce the depth of case required (fig. 4). On the dissociation of the ammonia the nascent nitrogen is diffused into the outer layers of the steel and combines with the alloying elements to form nitrides. No further treatment of any kind is required and the parts are allowed to cool in the box. The process produces remarkable surface hardness and resistance to wear and abrasion without warping or distortion; in fact, the wear resisting properties are greater than those obtained by any other process. The physical properties which have previously been established in the steel are retained unimpaired in the core. The case or surface produced is also highly resistant to corrosion; this is a valuable characteristic which accounts for the increasing use of the nitrarding process for pump shafts and other parts which are exposed to water and atmospheric corrosion. Chief among the advantages of being able to harden steel so effectively at so low a temperature and without

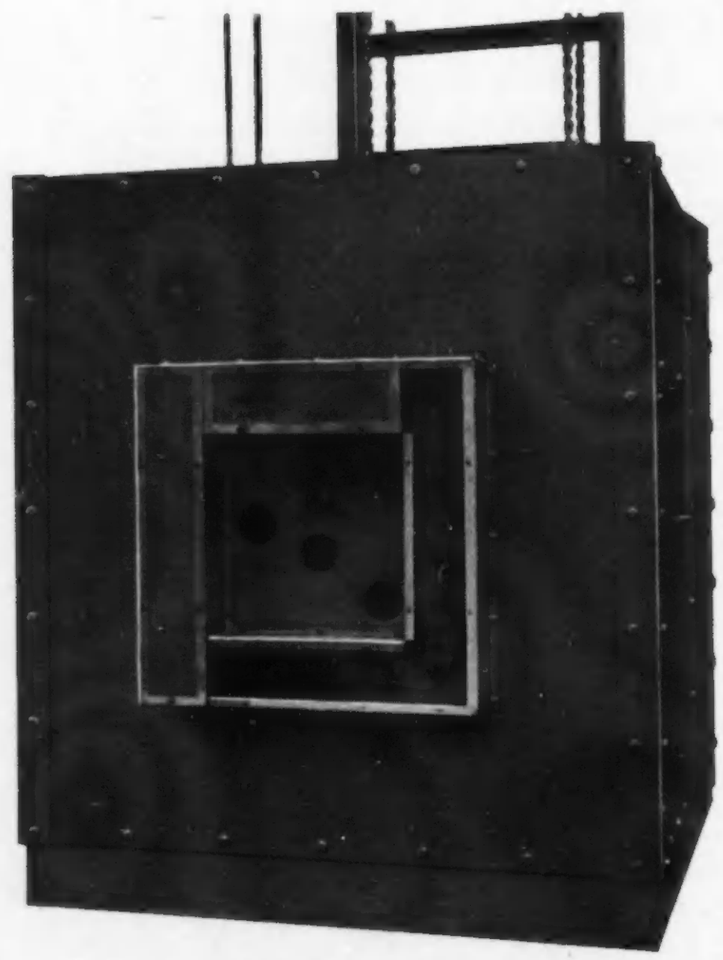


Fig. 5.—Rear view of electric nitrarding furnace, showing openings for ammonia inlet and outlet pipes, thermo-couple, etc.

subsequent quenching or other treatment, is the ability to harden in the finish-machined condition without distortion, deformation or quenching cracks.

The diagram in fig. 6 shows graphically the relative hardness of nitrarded steel from surface to core. It will be seen that the maximum hardness is immediately below the surface from which point it

tapers off gradually towards the core. The absence of any sharp line of demarcation between the case and core is a very desirable feature as it ensures freedom from peeling or spalling.

The equipment required for this process consists essentially of an electric furnace provided with automatic temperature control, a gas-tight box made of heat-resisting alloy which is capable of withstanding the action of ammonia at nitrarding temperatures, an ammonia vessel with control valve, together with the necessary tubes and simple apparatus for determining the extent of the dissociation of the ammonia, etc.

Electric furnaces are used exclusively for nitrarding because it is essential that the heat distribution should be uniform and the temperature unvarying throughout the duration of the process. These exacting conditions are met by the electric furnace which is independent of manual operation or skilled supervision. A temperature variation which would be considered small in a fuel-fired furnace has an appreciable influence on the rate of dissociation within the box. A comparatively small increase in temperature reduces the hardness of the case considerably. Electric nitrarding furnaces are of two main types, the horizontal box type and the vertical cylindrical type. Within its own field and range of application, each has its particular advantages. The constancy of flow of the ammonia and its uniform distribution over the entire surface of every piece within the nitrarding box are just as important as precise temperature control. Experience has shown that the shape and size of box are important

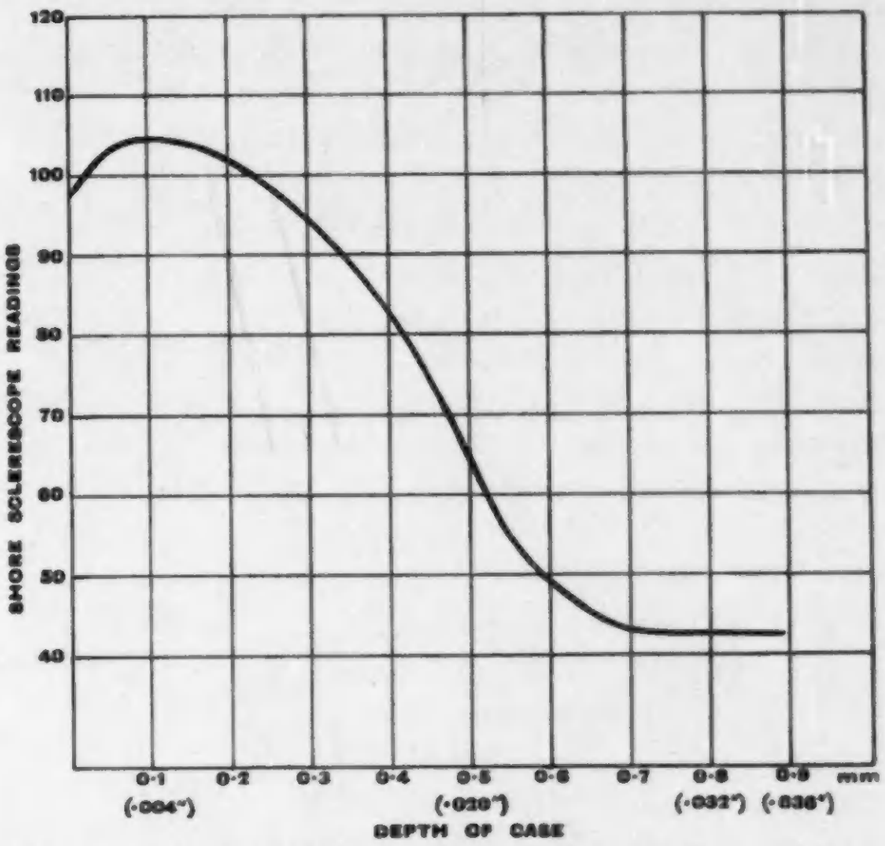
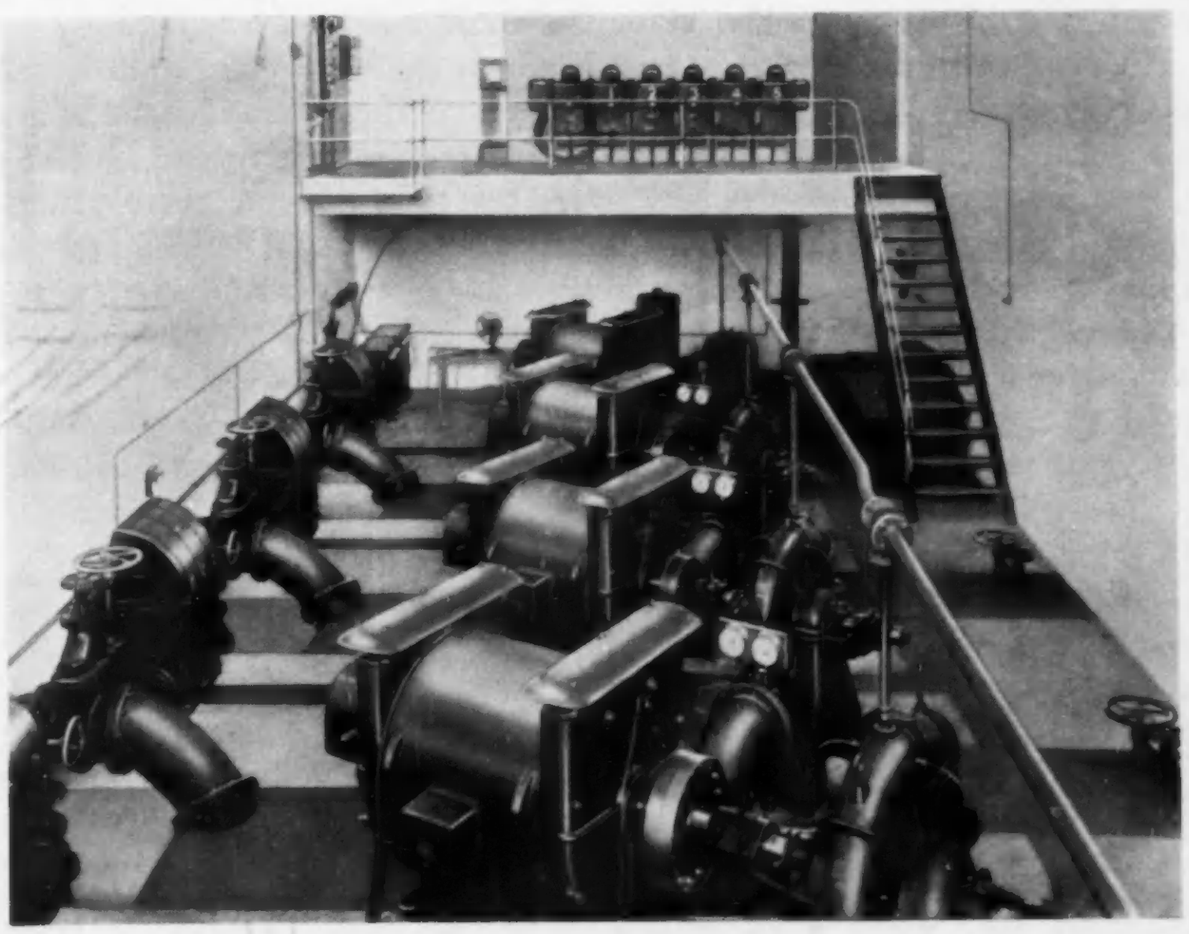


Fig. 6.—Relative hardness of nitrarded steel from surface to core.

factors in securing these conditions; hence the development of the two types to meet varying requirements. In some instances it is even found advantageous to mount a fan within the container in order to ensure uniform gas distribution.

Pumping Equipment for Benares Water Works, India.



View of the Bhelupura Pumping Station of the Benares Water Works. The equipment installed includes three 250 and one 350 h.p. G.E.C. slipring induction motors, rated at 2,300 volts, 3 phase, 50 cycles, 980 r.p.m., which are coupled to Worthington Simpson pumps capable of delivering 3,600 gallons of filtered water per minute against a head of 135 feet

Soot—A Commercial Product.

THE MANUFACTURE AND USES OF CARBON BLACK.

By the late W. E. DOWNEY, Ph.D., D.I.C.

Research Laboratories of The General Electric Co., Ltd., Wembley, England.

W. E. Downey was a brilliant young chemist who joined the staff of the Wembley Research Laboratories after a distinguished career at the Imperial College. For some years he had been in the closest contact with the problems of the manufacture of applications of carbon blacks.

This article, in which he has so ably crystallised his knowledge of the subject, was completed only a few days before his tragic death on the Jungfrau at the early age of 31.

(1). INTRODUCTION.

THE word soot suggests smoke, that by-product of combustion which causes so much trouble in modern cities. It may seem strange, therefore, that while strenuous efforts are being made to eliminate soot as a nuisance, some 100,000 tons per annum are specially made for various purposes. This large amount is the present day output of an old industry, for the earliest users of soot were probably the Chinese, the beginnings of whose ink manufacture are lost in antiquity. The invention of ink is sometimes ascribed to Tien-Tcheu (2600 B.C.) and although the recipes were kept secret, the general principle was to make soot by burning a suitable oil such as sesame oil, after which the soot was mixed with gums. The blackness of the ink and its miscibility with water without sedimentation were two properties which varied with the skill of the craftsman. Later or probably contemporary discoverers of the use of soot were the Egyptians, whose earlier papyri are written with carbon ink. Lucas records examining a sample of black ink from an inkstand of the time of Amenhotep III (16th Cent. B.C.) which was essentially carbon. A method of preparation given by a priest of the Coptic church and, therefore, probably Egyptian in origin, runs as follows :— "Put a quantity of incense on the ground and round it place three stones, and resting on these an earthenware dish, bottom upwards, covered with a damp cloth. Ignite the incense, soot is formed and deposited inside the dish from which it is removed and made into ink by mixing with gum arabic and water." Coming to more recent times, we find that the Romans were conversant with the uses of soot and a good description of its manufacture is given by Vitruvius, a Roman architect of the time of Augustus. Vitruvius wrote the following about 25 B.C. "I have now to speak of those bodies which from particular treatment change their qualities and acquire colour; and first, of black which is employed in different works, in order that it may be known how it is prepared for use. A small room is built similar to a bath-room, plastered with marble stucco and polished. In front of it is built a furnace which communicates with the room; the mouth of this is very carefully closed for the purpose of preventing the escape of the flames. Resin is then placed in the furnace, whose smoke when the material is set in fire passes by means of communications into the room and therein adheres to the wall and arched ceiling. It is then collected and some part of it is tempered with gum to make ink for the transcribers; the remainder is used by stuccoers in colouring walls, being previously mixed with size. But if this cannot be procured, in order to prevent delay, the following expedient may be adopted. Pine branches or chips must be burnt and when thoroughly charred, pounded in a mortar with size. Thus the plasterer will procure an agreeable colour. A black colour not less pleasing is made by drying and burning the lees of wine in a furnace and grinding the result with size; indeed, this makes a very agreeable black. The better the wine whose lees are used, the better will be the black colour which will, in such case, approach the colour of indigo." This description is interesting because large quantities of soot are made to-day by the first of the above methods.

(2). CARBON BLACK.

Soot consists mainly of carbon, one of the more abundant elements of nature. The element carbon exists in two forms; one, diamond, has been esteemed from time immemorial as a precious stone, the other is graphite or plumbago. Until recently, a third form was generally recognised. Amorphous carbon was the term used to embrace substances such as bone black, charcoal, coke and soot. These bodies consist to a greater or less extent of carbon in an apparently non-crystalline condition. Mineral matter is usually present but even when it is absent or has been removed, the "carbon" rarely is pure. Small amounts of hydrogen invariably occur in "amorphous carbon." However, it is possible to obtain "amorphous carbon" which contains more than 99.5 per cent of carbon and no mineral constituents. Such carbon appears quite different from diamond or graphite, but it will be shown later that there is considerable evidence for supposing that it consists of ultra-microscopic crystals almost identical in their internal construction with those of graphite. Purified soot is an example of this form of carbon, but to avoid confusion, we will now discard the word soot with its suggestion of the domestic fire and factory chimneys, and use the lesser known technical terms with their limited, defined meanings. The name carbon black* may be used to define a class of products each of which consists essentially of carbon in a very fine state of division (the upper and lower limits of the "diameters" of the particles may be taken as 10^{-4}cm. and 10^{-6}cm. respectively, and the lower limit of the carbon content as 90 per cent). This form of carbon is formed by the incomplete combustion of the vapours of non-metallic carbon compounds or by the direct decomposition of such vapours. The finely divided carbon so made first owed its importance to its usefulness as a black pigment, but in recent years other uses have been found. The older method of manufacture was to use oil, usually coal tar oil, as the fuel in conjunction with a furnace and collecting chamber similar to those described by Vitruvious. Carbon black prepared in such a manner was, and is known as *lamp black*. From 1870 onwards, however, a different raw material and method came increasingly into use so that to-day some 95 per cent of the total world production of carbon black is made by this second method. The method arose out of and depends on the abundant supplies of natural gas which occur in the United States.

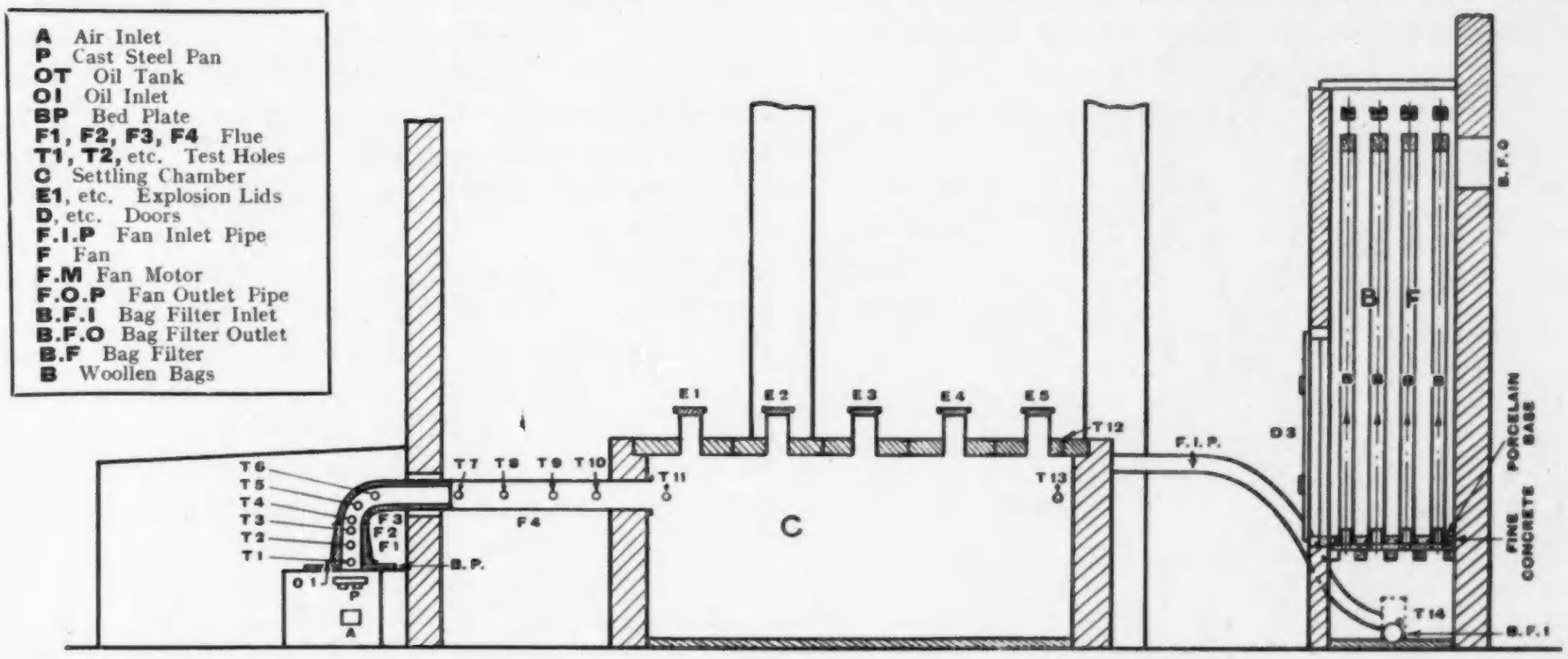


Fig. 1.—Diagrammatic section of a carbon black producing plant.

Natural gas usually consists of 95 per cent of methane, although sometimes considerable amounts of ethane are present. The gas is allowed to burn with a small flame which impinges on a relatively cool iron surface. Carbon deposited on the surface is scraped off and forms the commercial product commonly known as *gas black*. Speaking quite generally, gas black is blacker, and appears more dense than lamp black, has a metallic sheen and is wettable with water. The size of the particles is less than that of lamp black particles. Fifty years ago gas black cost about 10/– per pound, but by 1912 the price had fallen to 2½d. per pound. Subsequent to the discovery of the re-inforcing action of finely divided carbon on rubber (Silvertown Rubber Co., 1914), the price and demand rose. The U.S. Bureau of Mines reported some 200 million pounds to have been made in 1927 and the price to-day is approximately the same as in 1912.

In this article we shall discuss the uses, manufacture, and nature of carbon black and attempt to indicate the underlying causes of its commercially valuable properties.

* The definitions used in this article are generally recognised in England, but differ from those of American practice. In the United States gas black and carbon black are synonymous; carbon black is the more commonly used term for black made by impingement. There appears to be no term used in America for the class of products as defined above.

(3). USES OF CARBON BLACK.

(a) Miscellaneous.

The better grades of arc lamp carbon electrodes demand for their manufacture a basis of carbon which contains as little mineral matter as possible. Gas retort coke and petroleum coke rarely are pure enough, so that resource is usually had to lamp black. Some time before the War the G.E.C. built a lamp black plant at Witton to make carbon for its Carbon Works, and during the War this plant was considerably extended to supply rubber manufacturers with the newly discovered reinforcing filler. In connection with the electrical industry, another possible direct use for carbon black has recently been suggested by Wiegand, Boggs and Kitchen. These authors claim that the electrical breakdown strength of a series of transformer oils

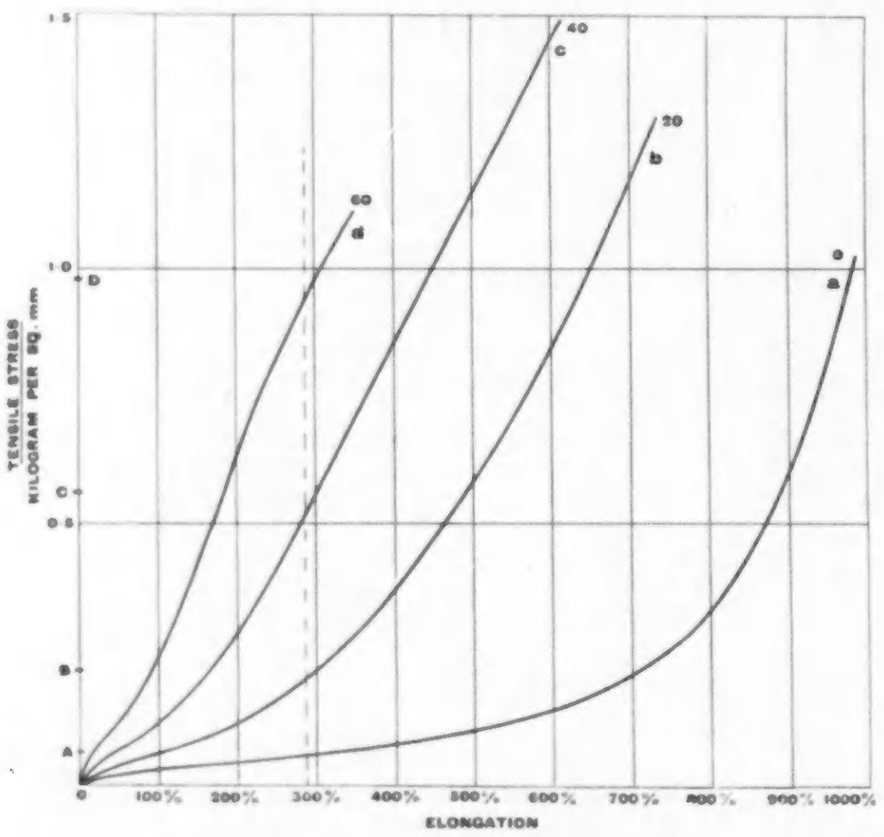


Fig. 2.—Effect of increasing amounts of lamp black on tensile strength of a rubber-sulphur mix.

was raised by an average of 40 per cent after treatment by various methods with carbon black, the action being one of removing moisture and/or electrolytes.

Of the non-electrical secondary uses of carbon black, it will perhaps suffice to mention a few. Shoe and stove polish, gramophone records, black paper and non-dazzling concrete roads are but examples of the wide range of products containing carbon black.

(b) Rubber.

The chief use for carbon black to-day is as a reinforcing filler in rubber compounding. Raw rubber vulcanised by heating with a small amount of sulphur yields a product which has great elasticity and small rigidity. For some purposes, notably for pneumatic and solid tyres, floors and shoe soles, it is desirable to produce a more rigid product than can be obtained from rubber alone. Almost any finely divided inert powder will produce the desired result as far as hardness and rigidity are concerned, but a few substances, in addition to producing rigidity in the vulcanised rubber, increase the tensile strength and the resistance to abrasion. Such *reinforcing fillers* include magnesium oxide, zinc oxide, litharge and, most influential of all, some carbon blacks. Fig. 2 shows the effect of increasing amounts of lamp black on the tensile strength of a given rubber-sulphur mix. Concurrently with the alteration in tensile strength there is a change in the rigidity as measured by the force necessary to stretch a test piece to say, 300 per cent. extension. The dotted line in fig. 1 cuts the stress-strain curves at equal strain so that the corresponding stresses (A, B. C. & D) indicate the rigidities of the different mixes. It is useful in assessing the reinforcing action of a filler to consider the integral of stress with respect to strain between the limits, no strain and breaking strain. This integral is a measure of the energy absorbed on stretching the rubber mix to its breaking point and the energy required to stretch unit volume of the mixture to the breaking point is termed the *resilient energy*. (The importance and meaning of this quantity is further dealt with in Section 6(b). Now if a wheel shod with rubber is rotated over a surface by the application of a torque to the axis of the wheel, the surface layer of the tyre is first compressed and then stretched as the tyre surface respectively approaches and leaves the road surface. If the energy transmitted through the surface layer of the tyre is less than that required to stretch the rubber to breaking point, then no rubber will be removed from the surface layer. If, however, the energy transmitted is greater than the resilient energy of the tyre tread, the tread will suffer abrasion. Thus a mixture which shows a high resilient energy will be expected to give good results as a tyre tread. A close correlation is found in practice between the life of a tyre tread, the resilient energy of the mix used in the making of the tread and the abrasion resistance of the mix as measured by grinding a sample of the mix under controlled conditions. Gas black generally produces a higher resilient energy than lamp black and hence, gas black is mainly used in pneumatic tyres. Gas black, however, has a disadvantage which becomes important when a thick layer of rubber mix is used as in a solid tyre. Gas black mixes under repeated compression and extension generate more heat than lamp black mixes, and the heat generated may, in the limit, cause a "blow out." The heat generated is related to the hysteresis in the stress-strain relationships during retraction after extension. Fig. 3 shows how the stress-strain relationships of a gas black

mix are further removed from reversibility than those of a lamp black mix. Such energy as is not returned on retraction is dissipated as heat but the cause of the hysteresis is at present not understood.

(c) Ink.

Printers ink used to be made from lamp black, but since the time of its first production, gas black has come increasingly into use because it yields an ink more suitable for the modern fast feeding newspaper presses. Some carbon blacks yield inks of a buttery consistency which do not flow well and are termed "short." The spreading power of suitable carbon black may be gauged from the fact that one pound of pigment with oil makes sufficient ink for 2000—2500 copies of a 16 page newspaper of normal size. The consumption of carbon black for ink manufacturers is quite large, although it is difficult to say what proportion of the total production is used for this purpose.

(d) Paint.

Carbon black made by both methods is used in the paint industry. Gas black, which is more intensely black in colour, is largely used to make enamels, although for some purposes lamp black, which has a blue "undertone" is preferred. The difference in "undertone" of the two pigments is clearly shown when they are used with a white pigment to make a grey paint. The blue-grey produced when lamp black is used is much more pleasing than the brown grey which results from gas black. Although colour may be regarded as of first importance in considering a pigment, ease of dispersion in the vehicle, non-segregation in storage and non-interference with the drying time are other desiderata. A striking example of these latter properties occurs in the use of carbon black in the manufacture of "leather-cloth" or "American cloth." Leather cloth is used for imitation patent leather, perambulator hoods and motor car fabric bodies, and consists of several layers of paint laid on a cloth foundation. The basic flexibility is partly due to the use of carbon black, although the surface colour and pattern often entails the use of other pigments. For economic reasons the drying time between the application of the various coats is closely defined so that the skill of the carbon black maker is strained to meet all the criteria outlined above.

(4). MANUFACTURING METHODS.

Carbon black manufacture is still a craft rather than a science. All but the simplest of combustion processes are beyond the scope of the scientist to explain, so that no reflections need be cast on the carbon black manufacturer for the crude and old fashioned plant he commonly uses. In the incomplete combustion method, a flame of the right size and shape is all that is needed. The direct decomposition or "cracking" method has promised for years to give much better efficiencies than the combustion method, in which of necessity some of the carbon of the fuel is converted into waste gases, but the difficulties of producing by this method a product free from ash and gritty coke have been so enormous that only a few processes have survived the crucial test, namely, the production of substance suitable for the rubber, paint or ink manufacturer. The following description of a few selected methods is perhaps preferable to a mere catalogue of processes tried or proposed.

(a) Lamp Black.

As has been mentioned already, the design of lamp black plants has changed very little with the

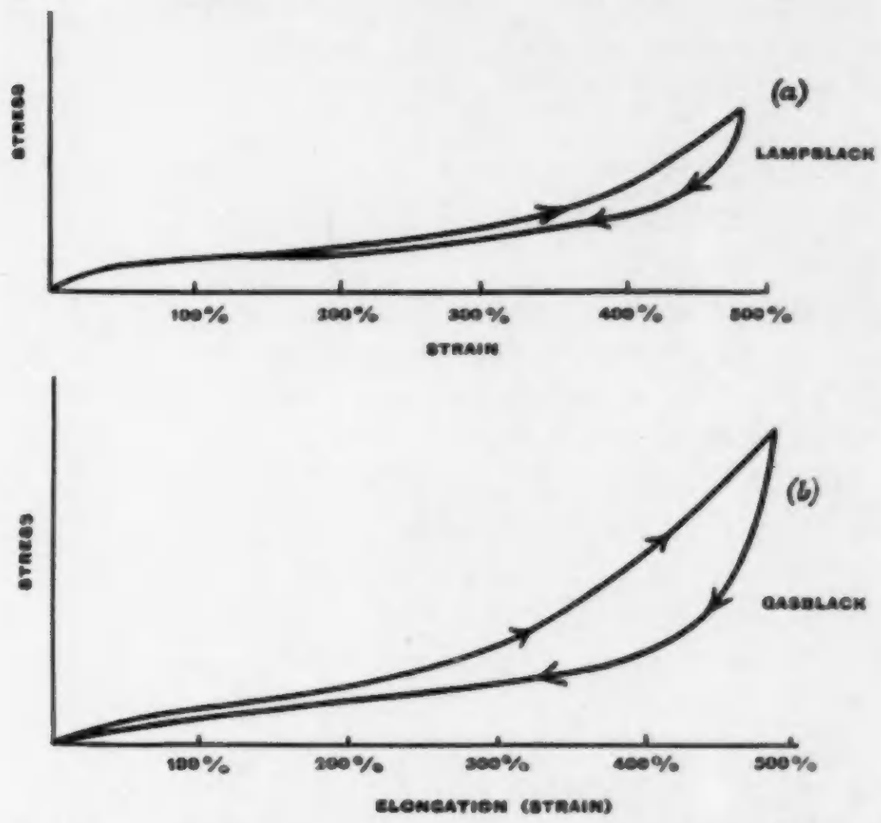


Fig. 3.—Illustrating how stress-strain relationships of a gas black mix are further removed from reversibility than those of a lamp black mix.

passage of time. Coal-tar creosote is a common fuel although water- and oil-gas, tar oils, heavy petroleum oils, anthracene and natural gas itself are alternatives which can be used. The manufacture of lamp black differs very notably from that of gas black in the size of the flame used. The liquid fuel is held in an iron saucer which may be any size from 12 to 60 inches in diameter (so that a flame is produced which is very large compared with those used in gas black manufacture). In one type of plant the saucer is placed in a vertical flue which communicates with a horizontal section leading to settling chambers. The top of the flues may be of brick or cooled iron. The smoky gases pass from the horizontal flue into a settling chamber which is of much greater cross sectional area than the flue and may be 10—30ft. wide, 10—20ft. high and 100—600ft. long. A hundred feet is not usually long enough for all the black to settle out on to the floor, so that if such

a short chamber is used, the dusty gas from the end of the chamber is passed into a bag filter where the gases escape through woollen bags whilst the black is retained. The draught necessary for the furnace is produced either by a chimney at the end of the settling chambers or by a fan, and in this latter case a second chamber or bag filter is placed on the outlet side of the fan to collect such black as may pass through the fan. The output from a unit depends on the number and diameter of the pans or saucers and on the grade of black which is produced. Whereas in a channel process gas black plant (see next section) 40,000 flames produce 3,000 lbs. of black per day at an efficiency of 2—5 per cent, the flame of one 5oin. pan will make the same amount of lamp black at an efficiency of 40—60 per cent. It will be clear from these comparative figures that it is only because the cost of natural gas is extremely low that the price of the two products is sensibly the same.

(b) Gas Black.

This type of carbon black is chiefly made in Louisiana and Texas, U.S., where natural gas abounds. Several designs of plant are used, but the process mostly employed is that known as the "channel" process. It is necessary to use vast numbers of small flames, produced by means of gas burners, similar to the old fashioned batswing burners, placed in rows some 3—4in. beneath a smooth surface in the form of channel irons. The channel irons are moved backwards and forwards past stationary scrapers which remove the soot deposited on the iron surface. The gas black so produced is conveyed to sieving and packing machines. A common size of unit makes 3000 lbs. of gas black per day and comprises some twenty-four buildings grouped together in which burn about 40,000 individual flames. Several units go to make up one plant which may have a capacity of as much as 50 tons per day, with a gas consumption of 60—80 million cubic feet. The efficiency of the process is low, being 2—5 per cent of the total carbon in the gas, but attempts to improve the efficiency almost invariably entail an alteration in the properties of the product with a decreased reinforcing action on rubber and since channel process black is the chief filler used in pneumatic tyre treads, this is not desirable. It was estimated by one of the leading suppliers that 60,000 tons of gas black were used in tyre manufacture in 1926; the corresponding amount to-day is certainly higher. Such an output meant the consumption of about one hundred thousand million cubic feet of gas.

Two variants of the channel process are the rotating disc and cylinder processes. The rotating disc is an annular one with the burners arranged in a circle underneath it. The black is deposited and collected in a manner very similar to that employed in the channel process. The yield and quality of the black is the same as that made by the channel process. In the rotating cylinder or roller process the burners are arranged beneath a rotating drum. The black made by this process is not used in rubber but for inks. Channel process black makes a "short" ink which does not flow so well as that made from "long" black such as roller process black.

(c) Other Methods.

Mention must be made of the efforts to produce gas black by a more economical process than the channel process. There are two reasons why so much time and money has been spent on thermal and electrical decomposition processes. In countries possessing a supply of natural gas, the low efficiency of the channel process is a source of anxiety both to the manufacturing and national authorities, since conservation of the resources is highly desirable. On the other hand, countries which do not enjoy the possession of natural gas desire to produce a suitable black which would render them independent. The yield from natural gas has been raised in two ways, but the product is not the same as channel process black, and approximates more to a lamp black. In both of these, a brick chamber is used; in one case it is made hot by the combustion of gas, after which the air is shut off, and the gas flow continued; in the other case, a small amount of air is admitted continuously and concurrently with gas. Both methods have been successfully worked, but the product is not so finely divided as channel black. The efficiency is about the same as that of a lamp black plant making low grade black.

The German and English chemical combines have in recent years taken out many patents for the use of carbon monoxide or mixed hydrocarbon gases in conjunction with catalysts. The catalyst usually consists of an oxide of iron, cobalt or nickel diluted with an alkaline earth oxide and activated by a small amount of an alkali metal oxide. The carbonaceous gases decompose in contact with the catalysts at 300—600° C., and the resulting gas black has to be washed with dilute acid to remove small amounts of entangled catalyst. Promising results have been obtained but the present low price of the American product renders all such complicated processes too costly. In one variation of the decomposition process acetylene is used. Acetylene gas blacks are made in small quantities but the price usually is high.

(5) TESTING OF CARBON BLACK.

In assessing the quality of any given carbon black various tests are applied, the most important of which are the following:—

(*a*) *Moisture* content, which often varies owing to the hygroscopic nature of some varieties.

(*b*) *Grit* consists usually of silicious matter or rust and is the percentage amount left behind on a sieve of given size of opening (90—200 per inch) when as much as possible of the sample has been passed through. Tyre manufacturers may demand a figure of 0.1 per cent on 100 mesh sieve.

blacks usually have little or no tinting strength. "High grade" carbon blacks are ones with a greater tinting strength than "low grade" carbon blacks.

(*f*) *Colour* is measured by comparing a paste of the sample in oil with some standard paste.

(*g*) *Oil Absorption* is the number of ccs. of raw

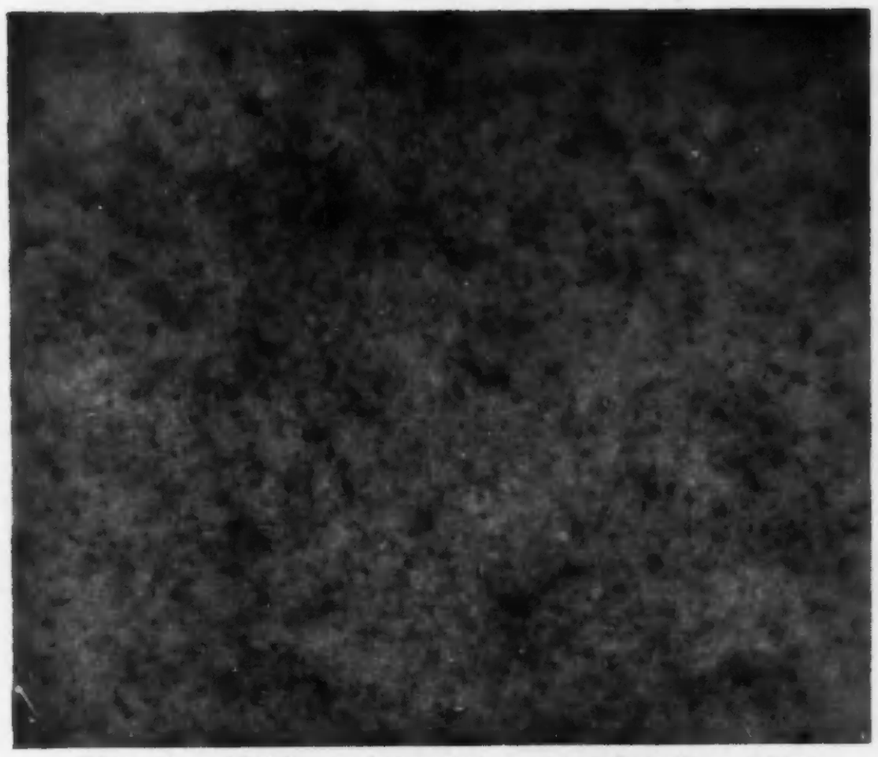


Fig. 4.—415H_2 paint, 2% magnification 1000. (Medium grade black).

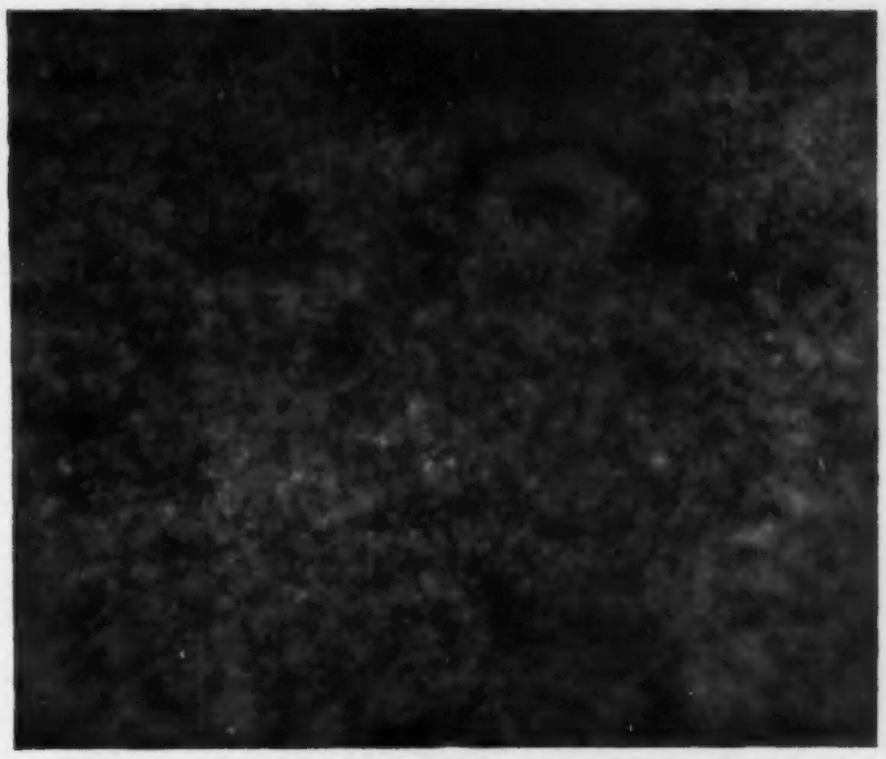


Fig. 5.—H.GH_2 paint, 2% magnification 1000. (High grade black).

Fig. 6.—MicH_2 paint, 2% magnification 1000. (Gas black).

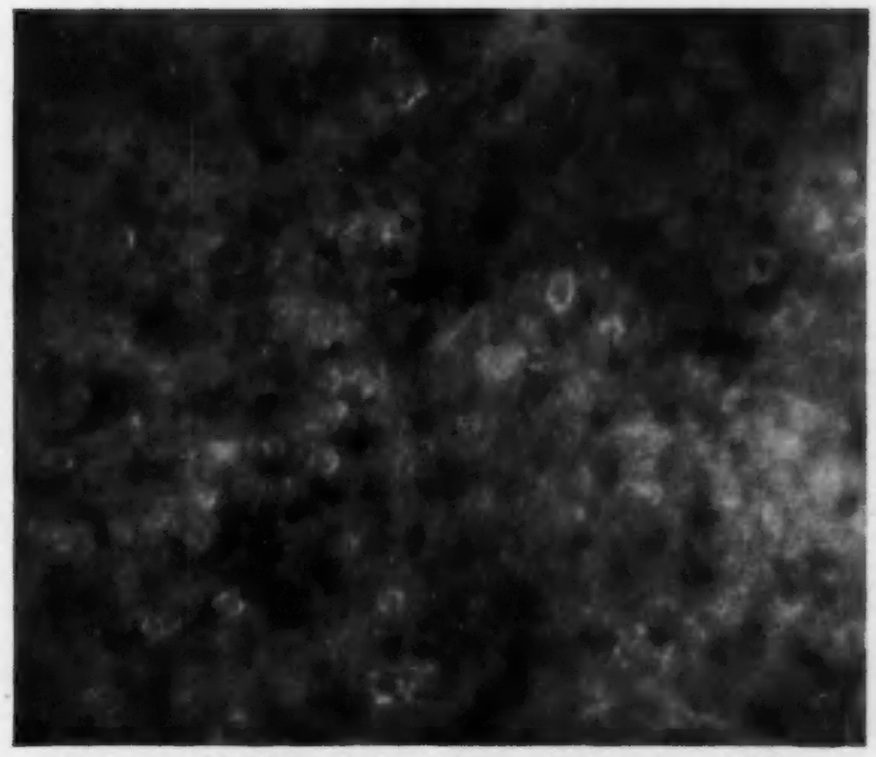


Fig. 7.—415H_2 paint, 2% magnification 2000. (Medium grade black).

Figs. 4 to 7.—Photomicrographs of various carbon blacks.

(*c*) *Ash*, the amount of non-combustible matter left after incineration, is usually less than 0.2 per cent if the article is genuine.

(*d*) *Oil* or matter soluble in some given solvent such as acetone rarely occurs in channel gas black but lamp black may contain up to 1 per cent.

(*e*) *Tinting strength* is measured by making a grey paint with zinc white containing 1 or 2 per cent of black and comparing the shade with some standard. Ground coal and mineral linseed oil necessary to make 100 grms. of black just adhere together. The amount varies from 100—350 ccs.

(*h*) *Bulk Volume* varies from 2 cc/gm. for a "heavy" black to 30 cc/gm. for a "light" black. This quantity must not be confused with the true specific volume which varies only from 0.5—0.55 cc/gm.

(6). THE NATURE OF CARBON BLACK.

(a) Chemical Composition.

It was stated in the introduction that carbon

black consists essentially of carbon in a very fine state of division. Table I exhibits the truth of the first half of this statement.

Table I.

TYPICAL COMPOSITIONS OF CARBON BLACKS
(Calculated on an ash-free basis).

	Carbon.	Hydrogen.	Nitrogen.	Sulphur.	Oxygen by difference.
Acetylene Black ..	99.80	0.20	—	—	—
Low Grade Lamp Black	98.08	0.67	0.23	0.60	0.42
High " " "	91.89	1.02	0.15	0.40	6.54
Channel Gas Black	95.72	0.84	0.03	0.03	3.38

Direct determination of oxygen shows that the amount varies with exposure in the case of some blacks. High grade lamp black and channel gas blacks adsorb oxygen and moisture. Thus, after exposing to air samples of the above blacks which had previously been dried, moisture and gas were absorbed to the extent shown in Table II.

Table II.

Loss in weight of Carbon Black on drying at 110°C.	
Acetylene black	0.06%
Low Grade Lamp Black	0.77
High Grade Lamp Black	3.59
Channel Gas Black	2.59

The effect of adsorption on composition is shown in the two following analyses which refer to gas black heated to 1,000° in hydrogen.

TABLE III.

Composition of Gas Black.
(After heating to 1000° in hydrogen).

	Unexposed to air.	Exposed for 10 minutes.
Carbon	98.93	94.77
Hydrogen	0.60	1.32
Difference	0.47	3.91

(b) Effect of Particle Size.

The second half of the definition of carbon black runs "in a very fine state of division." The various photomicrographs give evidence of the truth of this statement but comparisons may emphasise the point. Coal for pulverised fuel burners is often ground to pass a 300 mesh sieve. Such a sieve has openings 0.042 mm. or 42μ square. A low grade lamp black consists of particles whose average size is less than 0.5μ. Thus a space of one cubic millimetre, or the volume of a pin's head, would hold about 10^{10} such lamp black particles; alternatively, given a certain volume of coal ground to 300 mesh, a million times as many lamp black particles will be required to fill the same volume. Gas black particles are difficult to measure but various workers have found values for the "diameter" of 0.05 to 0.10μ. Certainly, these particles are well below the limit of microscopical resolution with visible light (0.2μ). The small size of carbon black particles means that a small amount by weight of the material covers a large area when spread out in a layer, a particle, or a few particles, thick. Here, then, is the reason for the immense tinting strength of carbon black. The finest of ground coal may appear black when viewed alone, but as soon as it is mixed with a fine white pigment, the lack of particle fineness compared with carbon black is evident in the very light grey colour which results. Conversely, gas blacks by virtue of the finer particle size show greater tinting strengths than lamp blacks. The effect of particle size on blackness *per se* is a little more complicated. All materials reflect some light when illuminated so that, given two surfaces made of a feebly reflecting substance, the one surface having a greater number of pits in it than the other, the surface with the more pits would be expected to trap more of the incident light by multiple reflections within the pits than the one with the larger pits. If now surfaces made of fine particles be considered, the finer the particle, the greater the number of pits in a surface made up of such particles, hence, less reflection. The close correlation between blackness and particle size is borne out by other considerations. The denser blacks show a copper coloured reflection when viewed at glancing angles. Now at large angles of incidence of light on a pitted surface, it can be shown that regular reflection occurs when $\kappa\lambda = 2D \cos i$ where κ = a constant small fraction, λ = wave length of incident light, D = depth of pits, and i = angle of incidence. It follows from this relationship that although no regular reflection takes place at small angles of incidence, at grazing incidence regular reflection takes place, which is reddish at first, becoming white as the angle increases. Further, since $D \propto \frac{1}{\cos i}$ for given λ, the angle at which the first reddish reflection occurs will be less for smaller particles (*i.e.*, smaller pits). Thus, gas blacks show red reflection with an incident beam further removed from grazing incidence than lamp blacks which require a greater angle of incidence for regular reflection. A further consideration is, however, necessary to cover the fact that, particularly amongst lamp blacks, two blacks may show blackness in the reverse order of their tinting strengths. Microscopical examinations of two such blacks reveals that one consists of dense compact particles, whereas the other is made up of fluffy or cellular particles. For example, of two lamp blacks made in two different furnaces, both had an average particle size of 0.36μ. The tinting strengths were about equal but the colour of one was much deeper than that of the other. That having the deeper colour had a bulk volume (inverse of apparent density) three times as great

as that of the other black and appeared much more flocculent under the microscope. Thus, although from the point of view of area covered per particle (*i.e.*, tinting strength) the less dense black was equal to the heavy black, the cellular particles of this black were more effective in trapping the light than the solid particles of the heavy black, and hence the less dense black appeared blacker. By making the less dense black into a paste with creosote and subsequently driving off the creosote by heating in hydrogen, there resulted a black of approximately the same colour as the untreated sample but of greatly reduced tinting strength due to agglomeration by removal of gas which normally kept the particles apart. Prolonged rubbing was necessary to break down the agglomerates to restore the tinting strength. The heavy black under similar treatment was not affected, presumably because its solid particles had no tendency to mat together.

The importance of particle size in conferring on carbon black its valuable properties is further emphasised when the action of this substance on rubber is considered. The addition of carbon black to a mixture of rubber and sulphur results in the formation of interfaces between the black and the base mix. If there is an attraction between the black and the rubber at the interfaces, work will have to be done to disturb the interfaces, and the additional amount of energy required to break a test piece is expended in overcoming the interfacial forces which resist disturbance.

If, whatever the concentration of black, the

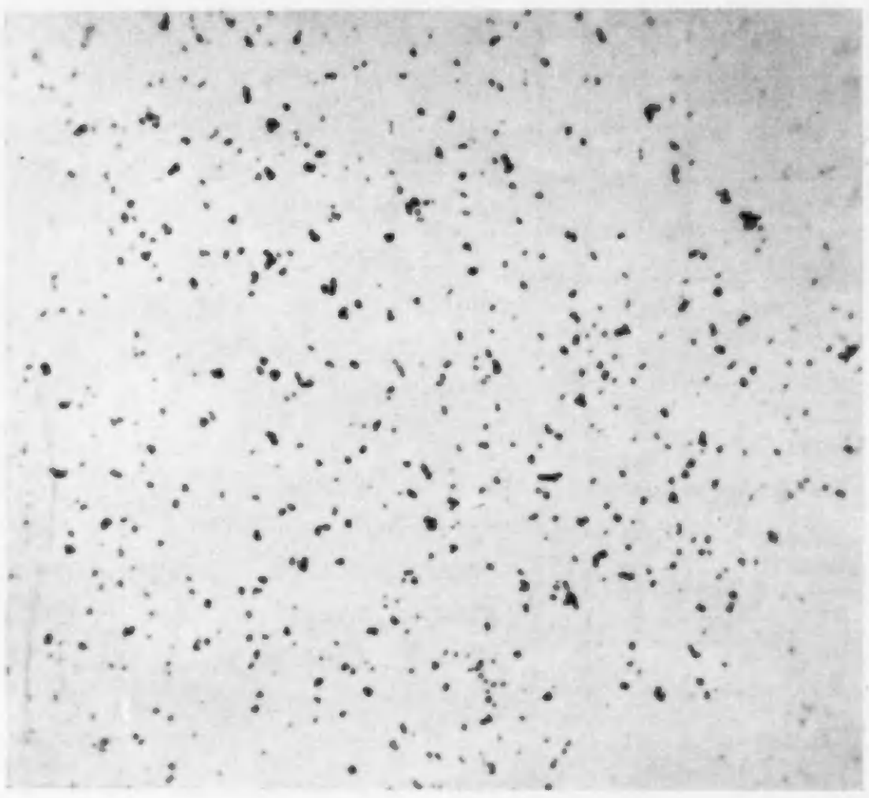


Fig. 8.—W. Black, 950°H_2. Magnification 1000.

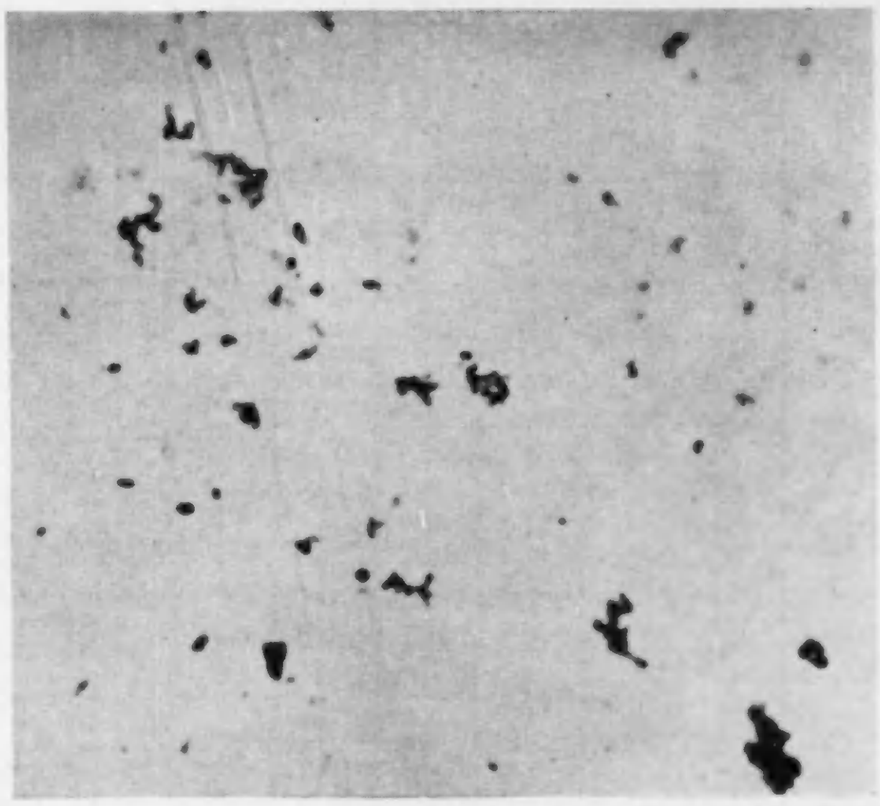


Fig. 9.—L.M. Co. Black 950°H_2. Magnification 1000.

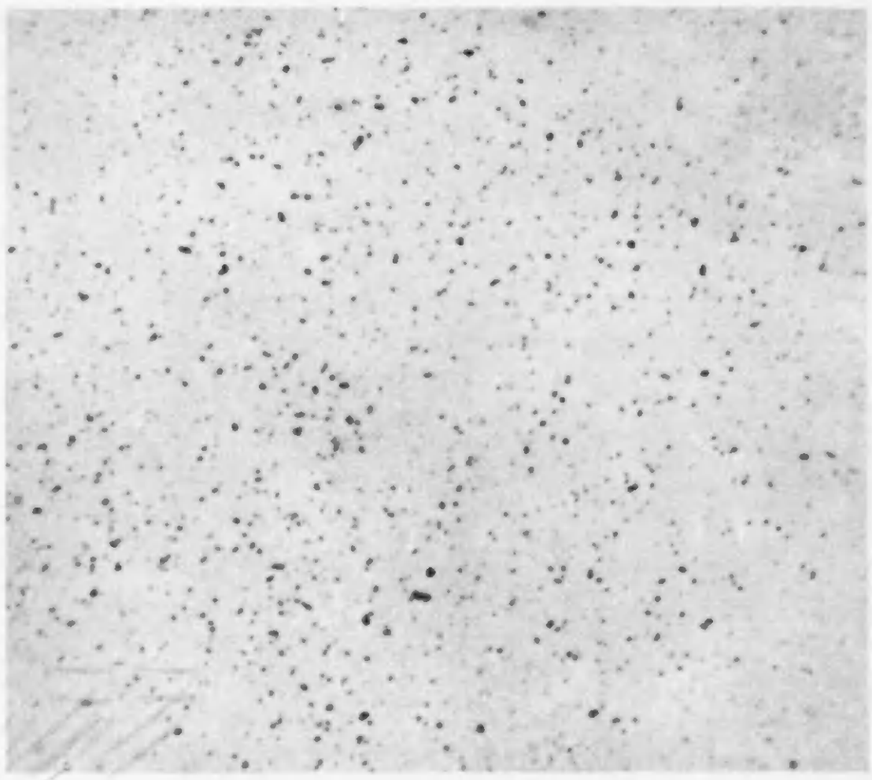


Fig. 10.—L.M.C. Black, 950°H_2. Magnification 1000.

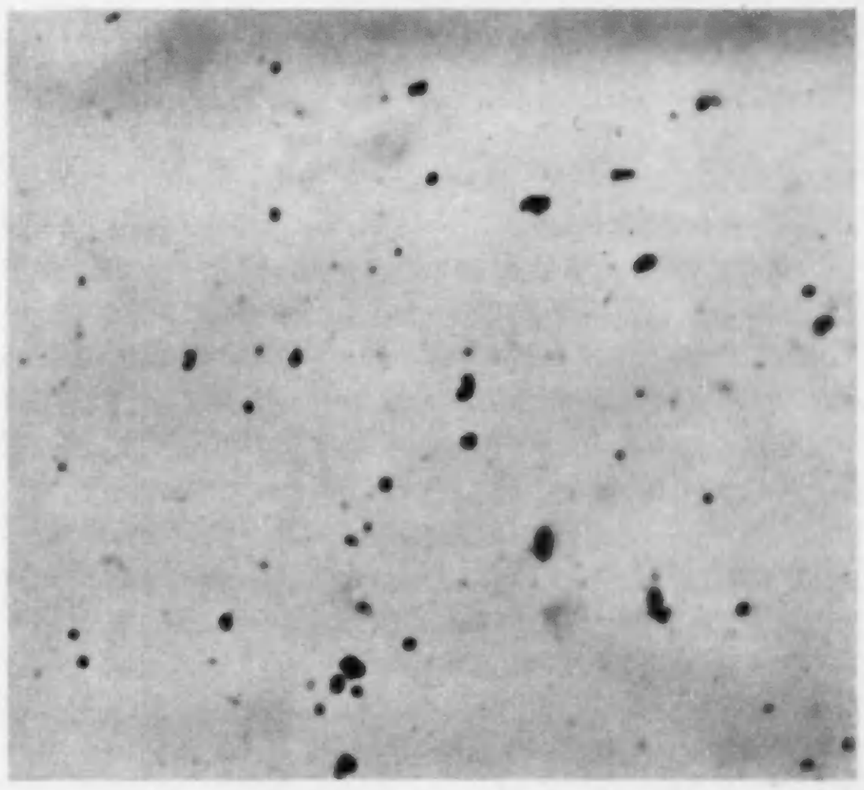


Fig. 11.—W. Black, H_2 treated. Magnification 2500.

Figs. 8 to 11.—Photomicrographs of various carbon blacks.

whole of the surface of the carbon black were in contact with the rubber, then the resilient energy (see Paragraph (3) (b) for definition) would continue to increase as more and more black was added. This is not found to be the case, for with increasing amounts of black the resilient energy reaches a maximum and then decreases. In mixes containing a high concentration of black, only a fraction of the black surface is adhering to the rubber, some of the aggregates of black are not broken up, and hence there are carbon-carbon as well as carbon-rubber interfaces. The energy required to separate a carbon surface from another carbon surface must be less than that required to separate carbon from rubber, otherwise dispersion would be impossible, and so it is to be expected that the resilient energy will decrease as the undispersed fraction increases.

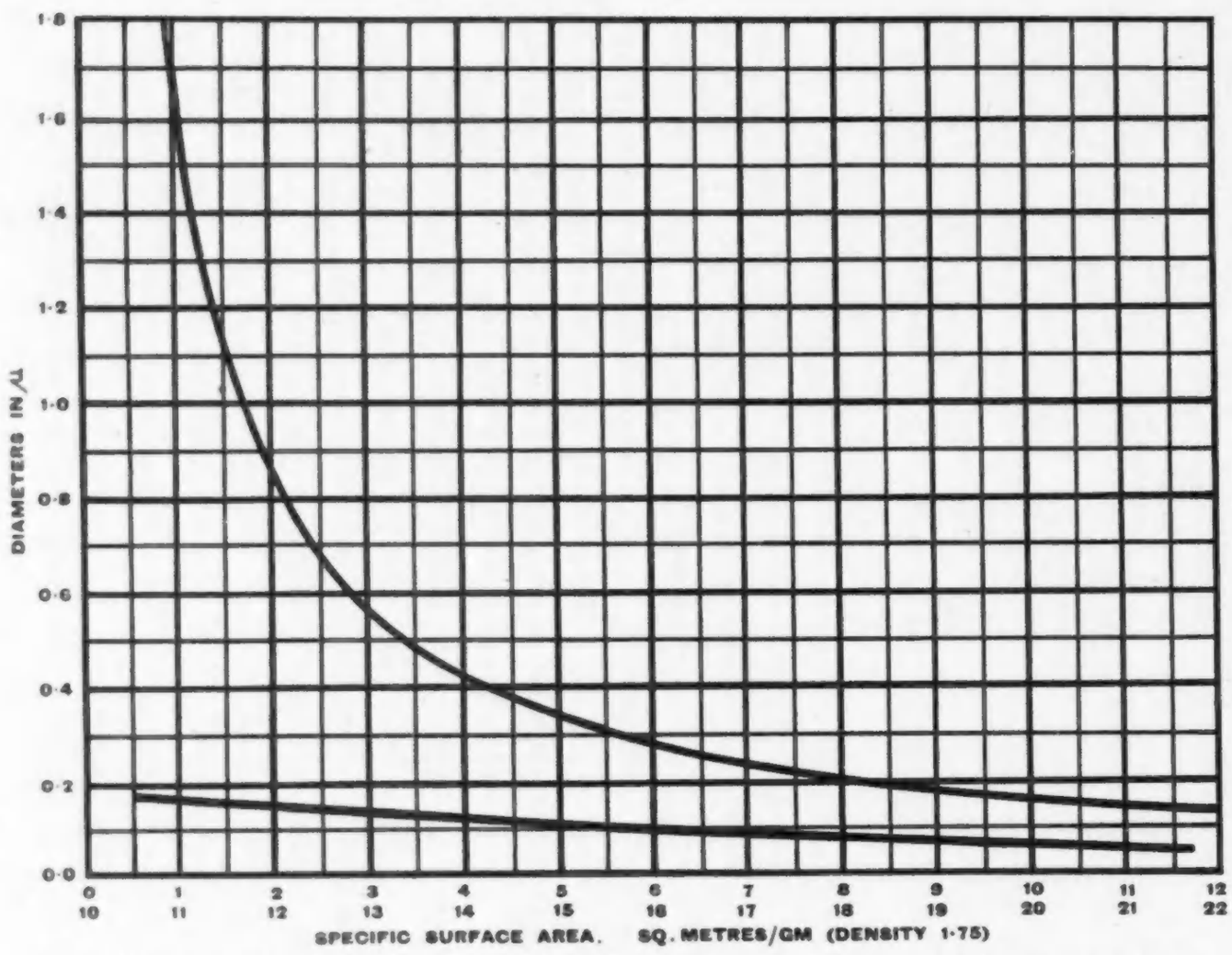


Fig. 12.—Relationship between specific surface area and diameters of particles.

At any given concentration of black in rubber, the amount of available surface of black will vary inversely as the mean diameter of black particles (fig. 12), consequently the resilient energy of a series of blacks, measured at the same concentration would be expected to increase with decreasing particle size, unless the dispersion of any given black was much more difficult to achieve than that of its fellows. Reference to fig. 13 shows that there is apparently little correlation between the resilient energies produced by given blacks and their particle sizes. Thus No. 2 black has practically no reinforcing power whatsoever, in spite of the fact that its particle size, measured in other dispersion media, is smaller than that of the other three lamp blacks.

This smallness of resilient energy may be due to one of two causes; either this black was very badly dispersed, *i.e.*, it was behaving as a black of comparatively large particle size, or else there is another factor which plays its part in determining the reinforcing power of a black. If the low resilient energy figure were due to bad dispersion, one would expect the mix containing No. 2 black to be similar in character to a mix containing a black of large particle size. This is not found to be the case, for the properties, other than resilient energy, of a mix containing No. 2 black are much nearer to those obtained with gas black. Moreover, this indirect evidence of dispersion is backed up by the fact that photomicrographs of dilute mixes in rubber show that the particle size is smaller than that of the other lamp blacks.

These data suggest that another factor, namely, the quality of the particle surface, plays a part in determining the reinforcing power of a black. If this is so, it should be possible, by changing the nature of the surface, to change the resilient energy of a mix of given concentration, and some recently obtained data of the resilient energies of different forms of No. 2 black, show that this can indeed be done. (See Table IV.)

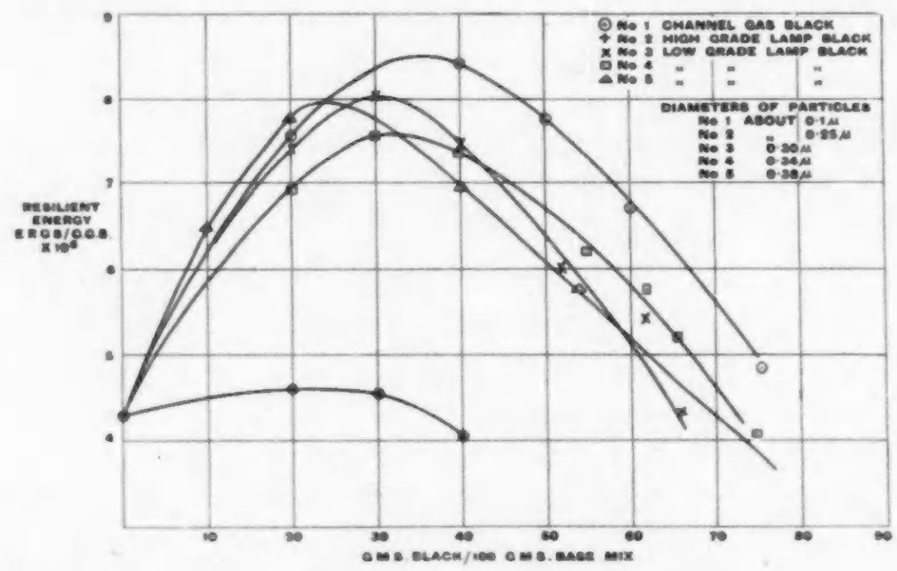

RESILIENT ENERGY ERGS/CC.S. X10⁶
No 1 CHANNEL GAS BLACK
No 2 HIGH GRADE LAMP BLACK
No 3 LOW GRADE LAMP BLACK
No 4 " "
No 5 " "
DIAMETERS OF PARTICLES
No 1 ABOUT 0·1 μ
No 2 " 0·25 μ
No 3 0·30 μ
No 4 0·34 μ
No 5 0·38 μ
10 20 30 40 50 60 70 80 90
C.M.S. BLACK/100 C.M.S. BASE MIX

Fig. 13.—Illustrating apparent small correlation between particle sizes and resilient energies of various carbon blacks.

It must be clearly understood that the exact part which carbon black plays in reinforcing rubber is not known. Experiments such as those just mentioned are being made by many people, but the craftsmen who make impinged gas black

obtain a product which the scientist at present cannot completely explain.

(c) Internal Structure of Carbon Black Particles.

The account of the nature of carbon black so far has been based on the following concepts :—

Table IV.

Resilient energies in ergs/cc. of mixes containing 40 parts of No. 2 black.	
Unchanged black	4.12×10^6
Treatment No. (a)	$5.31 \times$ „
„ „ (b)	$5.34 \times$ „
„ „ (c)	$7.4 \times$ „
„ „ (d)	$7.9 \times$ „

(1) A substance consisting of not less than 90 per cent of carbon together with hydrogen and, usually, oxygen.
(2) The substance has a high absorption for light.
(3) The substance occurs in the form of particles which rarely exceed 0.5μ and, less certainly, are greater than 0.05μ (5×10^{-6}cm.) in diameter.

The next stage is to consider how carbon atoms of 1.4×10^{-8}cm. diameter are arranged in groups of about a hundred million upwards to form the particles. The evidence is obtained from the way in which X-rays are reflected from the atomic planes in crystals. The X-ray patterns of carbon blacks are very similar to that of graphite crystals (fig. 14) which has been analysed into the structure shown

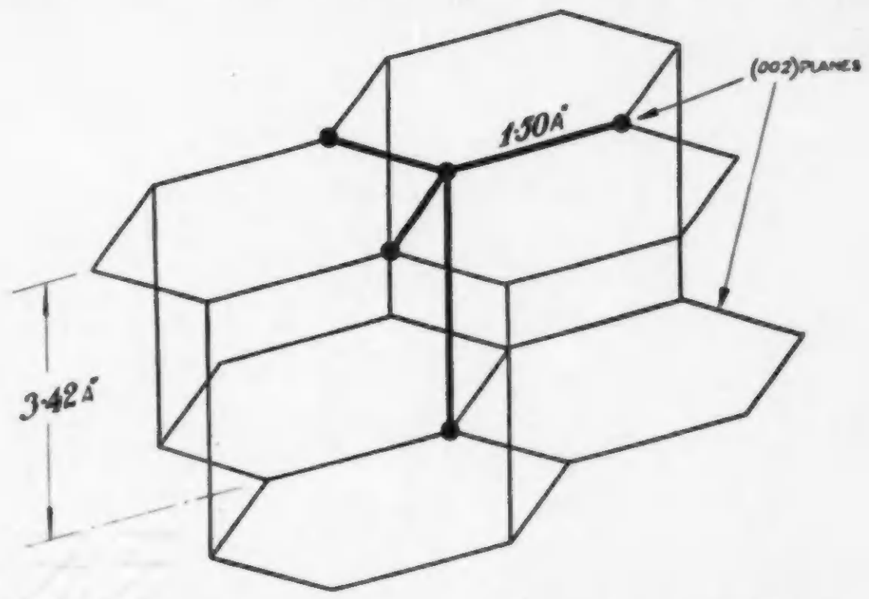


Fig. 14.—X-ray pattern of graphite crystals.

in fig. 15. The broad bands of carbon black patterns indicate that the reflections are coming from very small "crystallites" instead of the crystals which yield lines, as in the case of graphite. From the breadth of the band the size of the crystallite may be calculated, while from the displacement of the band relative to the corresponding lines of graphite, J. T. Randall and H. P. Rooksby have shown that the distance between the planes of hexagonally arranged atoms is greater for carbon blacks than for graphite. The higher the temperature of formation and the lower the adsorbed oxygen, the greater the size of the crystallites and the less the distance between the 002 planes (see fig. 14).

Herein lie some of the properties of carbon black. For example, since the separation of the 002 planes in carbon black is greater than in graphite,

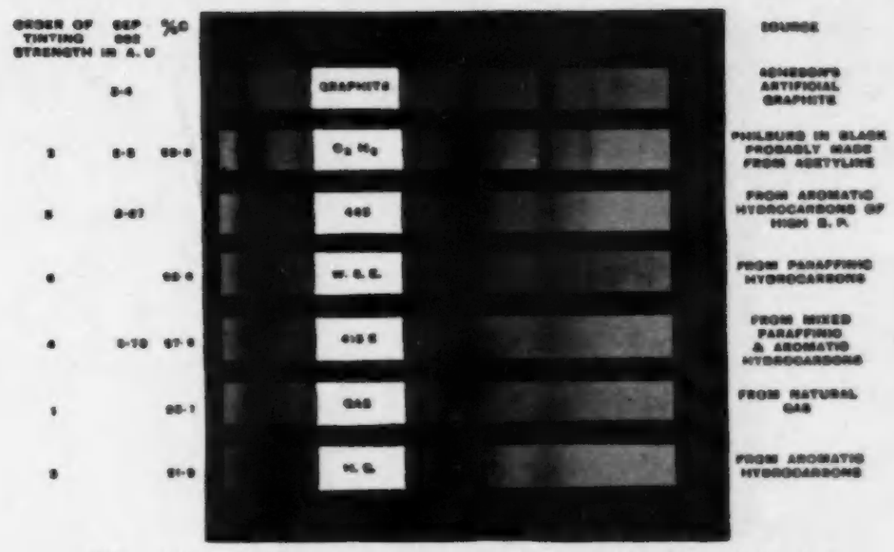

GRAPHITE
ACHESON'S ARTIFICIAL GRAPHITE
PHILBURO IN BLACK PROBABLY MADE FROM ACETYLENE
FROM AROMATIC HYDROCARBONS OF HIGH B. P.
FROM PARAFFINIC HYDROCARBONS
FROM MIXED PARAFFINIC & AROMATIC HYDROCARBONS
FROM NATURAL GAS
FROM AROMATIC HYDROCARBONS

Fig. 15.—Spectroscopic analysis of carbon blacks.

it follows that the number of atoms in a given volume is less, and hence carbon black should show a lower specific gravity than graphite. Thus from the gravity, 2.3, and a 002 separation, 3.4 A° (10^{-8}cm.), of graphite, it may be calculated that a similar crystal with a 002 separation of 3.5 should have a gravity of 2.15. Actually a black with this separation gave a specific gravity figure of 2.07. The explanation of the difference is probably to be found in the arrangement of the crystallites (10^{-6}cm. in size) into particles (about 2×10^{-5}cm.) containing ultra capillaries which were not filled with liquid in the specific gravity determination. Again, the varying distance apart of the 002 planes offers a reason why blacks do not always show adsorptive power proportional to the specific surface area (*i.e.*, area per gramme). Of two blacks, the one with a smaller 002 separation has a less residual attractive force at the surface of its crystallites than the one with greater 002 separation, and this effect must be set against any greater specific surface area due to smaller particles. Finally, the modification of the reinforcing power on rubber of a given black by heat treatment as previously mentioned, probably is connected with crystallite size and 002 plane separation, but it is as yet an unsolved problem.

(7). CONCLUSION.

In this account of "nearly pure carbon," some slight indication has been given of the problems confronting the scientist who tries to produce carbon black more efficiently or to utilise it more effectively. The little specks of dirt, be they destined for an arc lamp carbon or a car tyre, offer great scope for the investigator of to-day, and of to-morrow.

I wish to thank my colleague, Dr. F. S. Hawkins, for his assistance in those parts of this article dealing with the behaviour of carbon black in rubber.

A Ten Point Tandem Supervisory Control System.

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and

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WITH the rapid growth of electrical distribution systems and other public services such as water supply, sewerage, etc., the demand for some form of centralised control is becoming increasingly great. A great deal of development work has been carried out and many very comprehensive supervisory control schemes have been designed for controlling large distribution networks. There are, however, many other instances where remote control can be employed with advantage if the cost of the systems available bears an economic relation to the earning capacity of the plant.

In this article it is proposed to describe a simple, inexpensive and yet flexible method of remote supervisory control, and to show its application to the equipment of an A.C. rural distribution system, as there is certain to be considerable extensions of rural schemes in the near future.

A rural network will usually consist of one or more ring mains operating at 11 kV or 33 kV, with kiosks or pole-mounted tapping points at comparatively frequent intervals for the purpose of reducing the E.H.T. supply to feed in to the 400-volt, 4-wire network.

One of the chief difficulties in operating such a system is the maintenance of normal voltage at consumers' terminals within the limits laid down by the Board of Trade. Another difficulty is the rapid re-arrangement of circuits necessary to restore power after line trouble or any other disturbance which may have caused a failure of supply.

To maintain normal voltage at the consumers' terminals it is in most cases not possible to vary the ring main pressure with the rise and fall of load and it becomes necessary to fit each of the distribution transformers with on-load tap-changing gear, or to install induction regulators in the kiosks. From the above it will be seen that some form of remote control is very advisable and the system to be described is admirably adapted for use in such a case.

As is indicated by the title of this article, this is a tandem system, the pilot wires, which are four in number and common to all sub-stations, being looped into each point in any convenient manner and terminated at the control station. Thus when a new sub-station is installed it is only necessary to extend the pilots from the nearest existing point.

The maximum number of operations which can be performed is ten, which number it is considered will adequately meet the requirements of even the larger type of kiosk installation. For example, the following facilities might be provided, leaving one spare :—

(1). Raise the transformer ratio.
(2). Lower the transformer ratio.
(3). Indicate the transformer ratio.
(4). Indicate the system voltage.
(5). Close No. 1 circuit breaker.
(6). Trip No. 1 circuit breaker.
(7). Close No. 2 circuit breaker.
(8). Trip No. 2 circuit breaker.
(9). Telephone call.

The number of stations which can be worked in tandem on one pilot cable is theoretically almost unlimited, but practical considerations usually limit the total to approximately thirty.

METHOD OF OPERATION.

To each sub-station a number is allocated, consisting of two or three digits according to the size of the system. Each operation to be carried out at these stations is also numbered, but by a single digit only, the same number being employed as far as possible for equivalent operations at all stations.

At the point of control a dial of the automatic telephone type is provided, by means of which, after a start key has been operated, a station number may be dialled in the usual manner. This action causes impulses to be sent out over two pilot wires to all stations, where they are received by step-by-step selectors, each impulse advancing the

selectors by one step. Thus, on completion of a train of impulses all selectors will be resting in the same position.

By the setting of straps on a terminal panel each station is made responsive only to its allotted number, which, when received, prepares a local circuit condition enabling it to respond to further impulses. The receipt of the first dialled impulses at all stations other than that of which they constitute the pre-arranged number causes those stations to be locked out. Further, the receipt of the digits at the selected station is confirmed to the control point by a signal which is sent back and illuminates a check-back lamp on the control panel. For this back-indication a separate lamp is provided for each station so that if, due to faulty dialling or interference on the pilot wires, the wrong station is selected, the operator is warned by the illumination of the corresponding lamp. It would then be necessary to release the line and dial again before proceeding.

Having selected the station and received the correct check-back indication the operator will dial the number allocated to the particular operation it is desired to perform at that station. A further train of impulses will thus be sent out to the line but, as already mentioned, these impulses will be effective at the selected station only, where the selector will now be advanced to a position corresponding to the desired operation. When this is completed a check-back signal is again sent to the control station to indicate that the equipment is prepared correctly. This indication is also given by a lamp, associated with the selected operation.

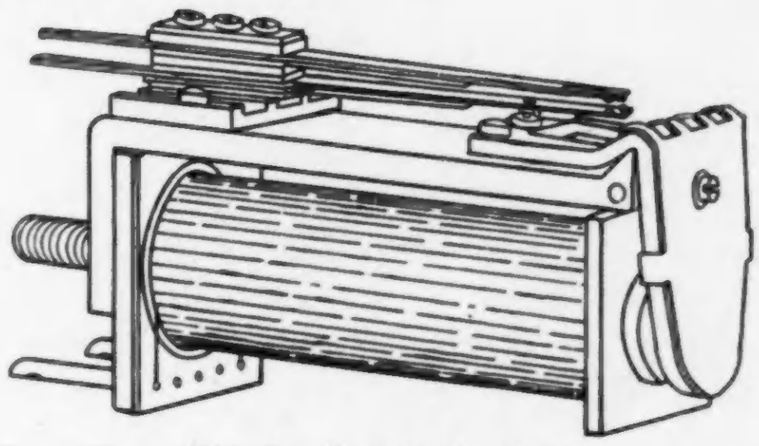

Fig. 1.—Standard relay.

Thus if it were desired to ascertain the position of the transformer tap-changing switch, the allocated number, say 5, would be dialled and, after the correct selection has been effected, the corresponding lamp on the control panel would light. But if for any reason the point associated with, say, the raising of the tap-changing switch had been selected, a separate lamp indicating preparation of the equipment for this purpose would warn the operator to release and dial again.

The second check-back signal having been received correctly, the desired operation is carried out by depressing an "operate" key which controls the functioning of a contactor associated with the point on which the sub-station selector is standing. In the typical case referred to above this contactor causes a device connected to the tap-changing switch to send back a signal to the control station, where one of a strip of lamps is illuminated to indicate the point on which the tap-changing switch is resting. On the release of the "operate" key the contactor releases and the indication stops.

The whole system can then be returned to normal by restoring the start key.

It will be noted that a dial has been specified as necessary for sending out the impulses required, firstly for selecting the station and subsequently the operation to be carried out. If

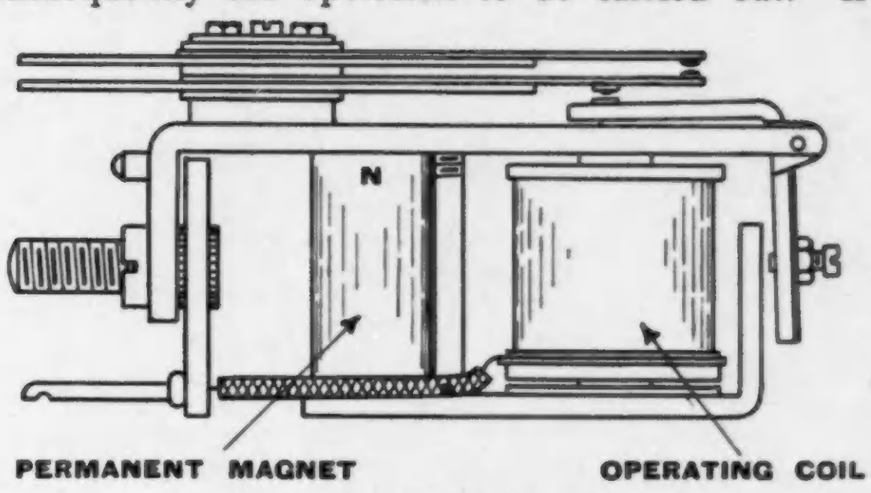

Fig. 2.—Polarized line relay.

desired, this piece of apparatus at the control point may be replaced by a set of telephone type keys, in which case a separate key would be provided for each operation at each station on the system. Instead of dialling the numbers, a station and operation would then be selected by depressing the appropriate key, an auxiliary equipment being provided to generate and control the impulses sent to the line. While to some extent this arrangement simplifies the procedure, it adds to the complexity of the system and increases the cost by an amount which, in many cases, may not be justified.

APPARATUS.

The control station equipment comprises :—

(*a*) A control panel.
(*b*) Relay and selector equipment.
(*c*) A 50-volt storage battery.
(*d*) Telephone instrument when required.

The control panel (*a*) in its simplest form consists of the wood front of a cabinet containing the relay and selector equipment (*b*), and carries the start and operate keys, the dial, two strips of check-back lamps (one for station check-back, one for operation check-back), and when required a further strip of lamps for tap-changing switch indication. There may also be mounted on this panel a chart showing the numbers allotted to the various sub-stations and operations.

The cabinet in which the relay and selector

equipment are mounted is of convenient size, measuring approximately 17in. × 24in. × 7in. In design the whole of the apparatus it contains is similar to that used in public automatic telephone systems, the principal types of relays being as shown in figs. 1 and 2. Contacts on all springs of these relays are of platinum and are duplicated to ensure freedom from faults commonly caused by dust and the presence of foreign matter. In order to give them a slow-to-release characteristic, some of the relays are also provided with copper sleeves surrounding their cores.

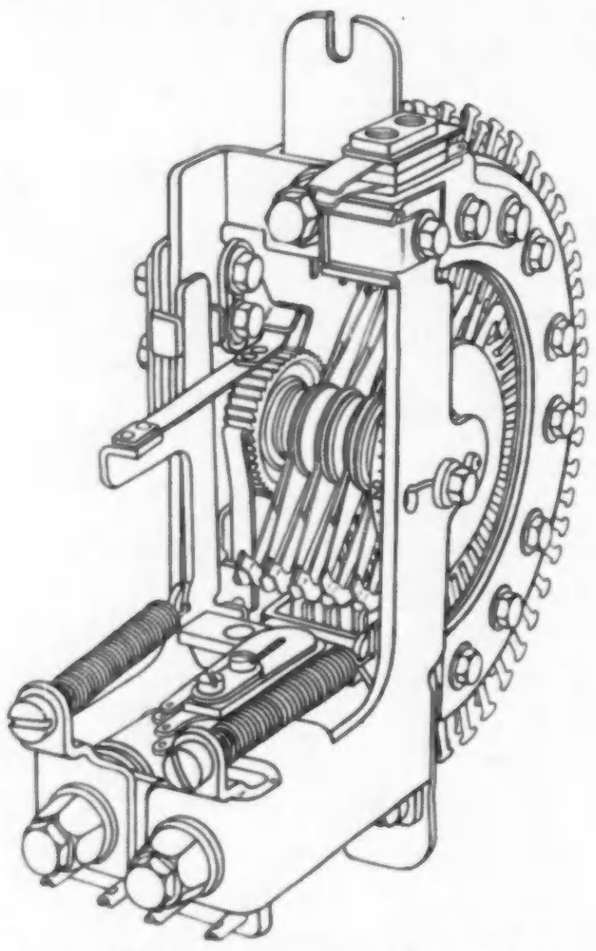

Fig. 3.—Control station rotary selector.

The selector (figs. 3 and 4) is a reverse drive rotary step-by-step switch. When the coils A are energised the armature B is attracted and pivots about the knife edge C against the pull of the helical springs H, attached to the frame D. An extension of the armature carries a flat spring E, to the extremity of which is connected the pawl F, engaging the ratchet G. A further extension T of the armature breaks the contacts V, when the armature is operated.

When the armature is attracted the pawl is carried into the next tooth of the ratchet, after which, when the coils are de-energized, the helical springs restore the armature to normal, thereby pulling the ratchet wheel one step forward. In this position it is held by the restraining pawl M. After each step a set of wipers K, clamped to the spindle of the ratchet wheel, is brought to rest centrally on a set of contacts L. Current is fed to the wipers by means of wire brushes R, running in grooved discs S to which the wipers are secured. The banks or arcs of insulated contacts are mounted on the frame N which is carried by the main framework of the cabinet, while the frame D carrying the selector mechanism is attached to the bank framework by the gland screw O and screw P. The mechanism is easily detachable and can be accurately positioned relative to the bank contacts by means of the gland screw. All mechanisms are interchangeable.

With regard to the 50-volt supply (*c*) it is usually desirable to provide a separate storage battery. Existing D.C. supplies might be used but it is considered advisable to keep the system independent of these, as it is at times when such supplies have failed that the equipment is particularly required. This 50-volt battery may be trickle-charged and of low capacity, say 10 ampere hours.

When provision is made for telephone communication between any or all of the sub-stations and the control operator, a telephone instrument (*d*) is included, working over the same pilot wires to all points.

The equipment provided at each sub-station consists of :—

(*e*) Relay and selector equipment.
(*f*) Such auxiliary contacts on the switchgear as may be required.
(*g*) A direct current supply.
(*h*) Telephone instrument when required.

The relay and selector equipment (*e*) is mounted in a wood case, 15in. × 20in. × 7in. and includes the numbering panel complete with an arrangement of straps by which means each station is made responsive only to its allotted number. The relays

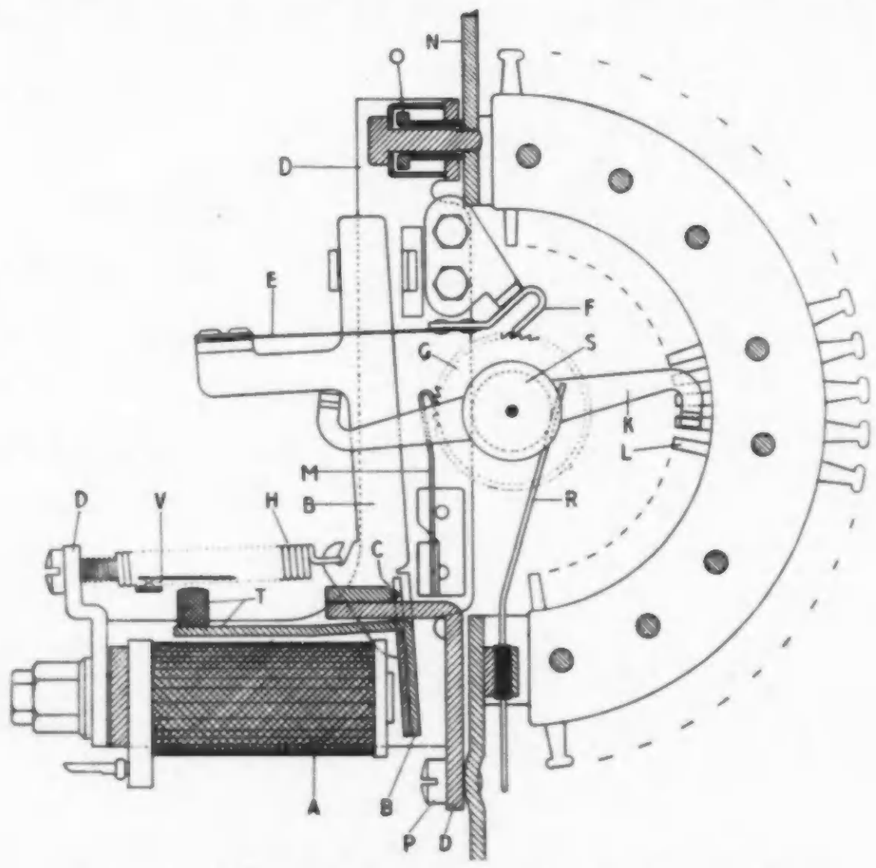

Fig. 4.—Mechanical details of rotary selector.

are of the types already described, but the selector is as shown in fig. 5. This switch, which is also of a design used in automatic telephony, consists of an arc of 11 contacts swept by a set of wipers clamped to a shaft carrying a ratchet wheel which is engaged

by the operating pawl. The operating pawl is pivoted on the extremity of the armature which is pulled forward under the control of the drive magnet against the tension of its return spring. The restraining pawl is kept in engagement with the ratchet wheel by a spring and is pulled out of engagement by energising the release magnet. A spiral spring housed within the hollow ratchet wheel, and having one extremity clamped to the ratchet and the other to the frame, is wound up as the wipers are advanced step-by-step over the arc of contacts. When the restraining pawl is withdrawn from the ratchet this spring returns the wipers to their normal position.

The auxiliary contacts (*f*) required on the switchgear are :—

For each circuit breaker—One pair of contacts made when the breaker is open, and one pair made when closed.

For each tap-changing switch—An auxiliary tapping switch geared mechanically to the tap-changing switch and making a separate contact for each position.

Depending on the size of the switchgear to be controlled, it may be necessary also to provide auxiliary contactors to step up from the voltages and currents carried by the contacts of the supervisory gear to those necessary for the operation of the switchgear. The contactors of the supervisory equipment, which form the link between the comparatively light telephone type apparatus and the switchgear, are capable of carrying and breaking 1 amp. at 230 volts.

The D.C. supply (*g*) required at each sub-station, preferably one of 24 volts, may conveniently be taken from the tripping battery, if available. If not, a trickle-charged storage battery may be used, or a rectifier and smoothing unit working from the A.C. mains.

The type of telephone instrument (*h*) recommended for the sub-station is made in a single unit containing the whole of the apparatus together with speaking batteries.

CIRCUIT OPERATION.

The simplified circuit diagram given in fig. 6 shows the principal details of the equipment necessary at the control station and one sub-station for carrying out the following operations :—

(1). Raising and lowering the tap-changing switch.
(2). Reading the low tension busbar voltage.
(3). Indicating the position of the tap-changing switch.
(4). Tripping the circuit breaker and indicating its position.

It will be assumed that the number allotted for selecting the sub-station shown is 37, and that the common digit 2 covers selection of the operation necessary to raise the tap-changing switch at any station on the system.

When the start key at the control station is operated, one contact of the key connects positive battery *via* the dial contact to relay D. Operated

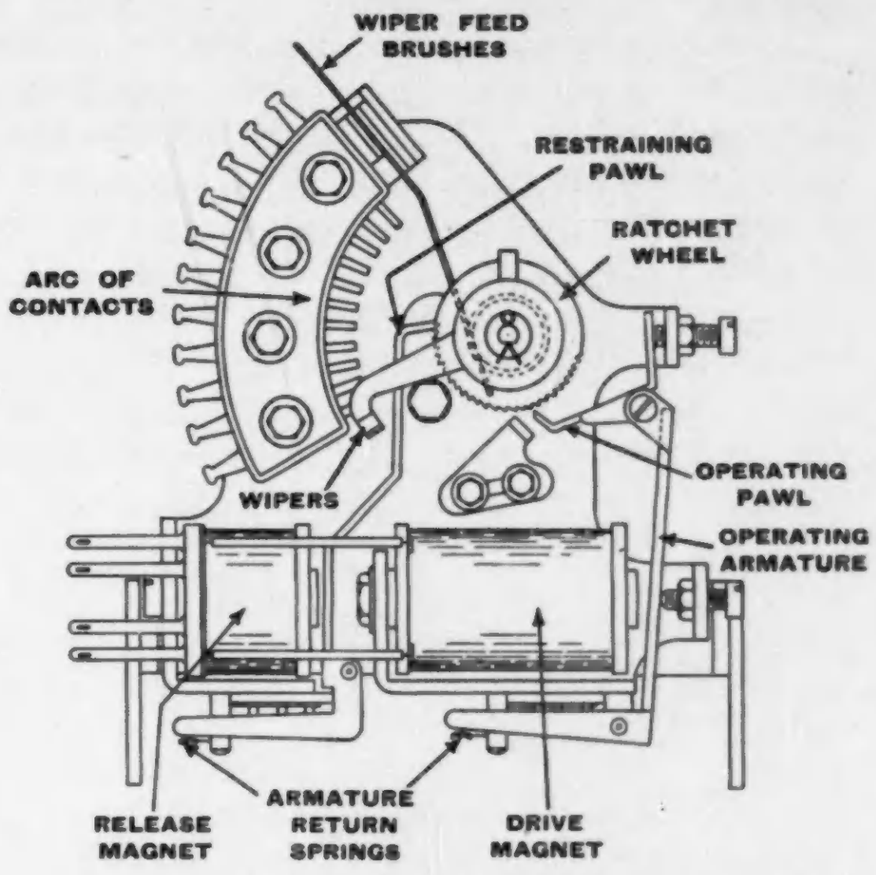

Fig. 5.—Sub-station selector.

contacts D1 and D2 connect positive and negative battery *via* the operated contacts of the start key and normal contacts of the operate key to lines C and A respectively.

At each sub-station a polarized relay L is bridged across these lines in series with a variable resistance X1 which is set at each station to allow equal currents to flow in all L relays. The polarity of the L relays is such that they operate with negative battery on the A line and positive on the C.

Operated contacts L1 at the sub-station connect positive to relay B which operates. Having its core surrounded by a copper sleeve relay B is of the slow-release type and will remain operated for some 200 milliseconds after current is cut off.

The station number 37 will now be dialled. With the finger first inserted in the hole numbered 3 the dial will be pulled round to the stop and released, whereupon the finger plate will run back to normal and cause the dial springs to be opened and closed three times. Thus relay D will release and re-operate three times. On each release of D, contacts D1 and D2 reverse the direction of current in lines A and C, and consequently in the polarized relay L at the sub-station, which will also be released three times.

On each release, normal contacts L1 complete a circuit from positive through operated contacts B1 to relay C and to DM which is the operating coil of the selector. Each time DM is operated the wipers of the selector will be advanced one step.

As each impulse transmitted by the dial consists of a period during which the dial contacts are closed for 33 milliseconds and open for 66 milliseconds, relay B remains operated over the open periods, and relay C, which is also slow to release, holds over the closed periods.

At the end of the train of impulses the selector will be resting in position 3, and after a short pause, relay C will release. While the selector was being stepped round, operated contacts C1 had removed positive battery from wiper 1, but this is now restored.

To make this station respond to its allotted number (37), the third strap on the numbering

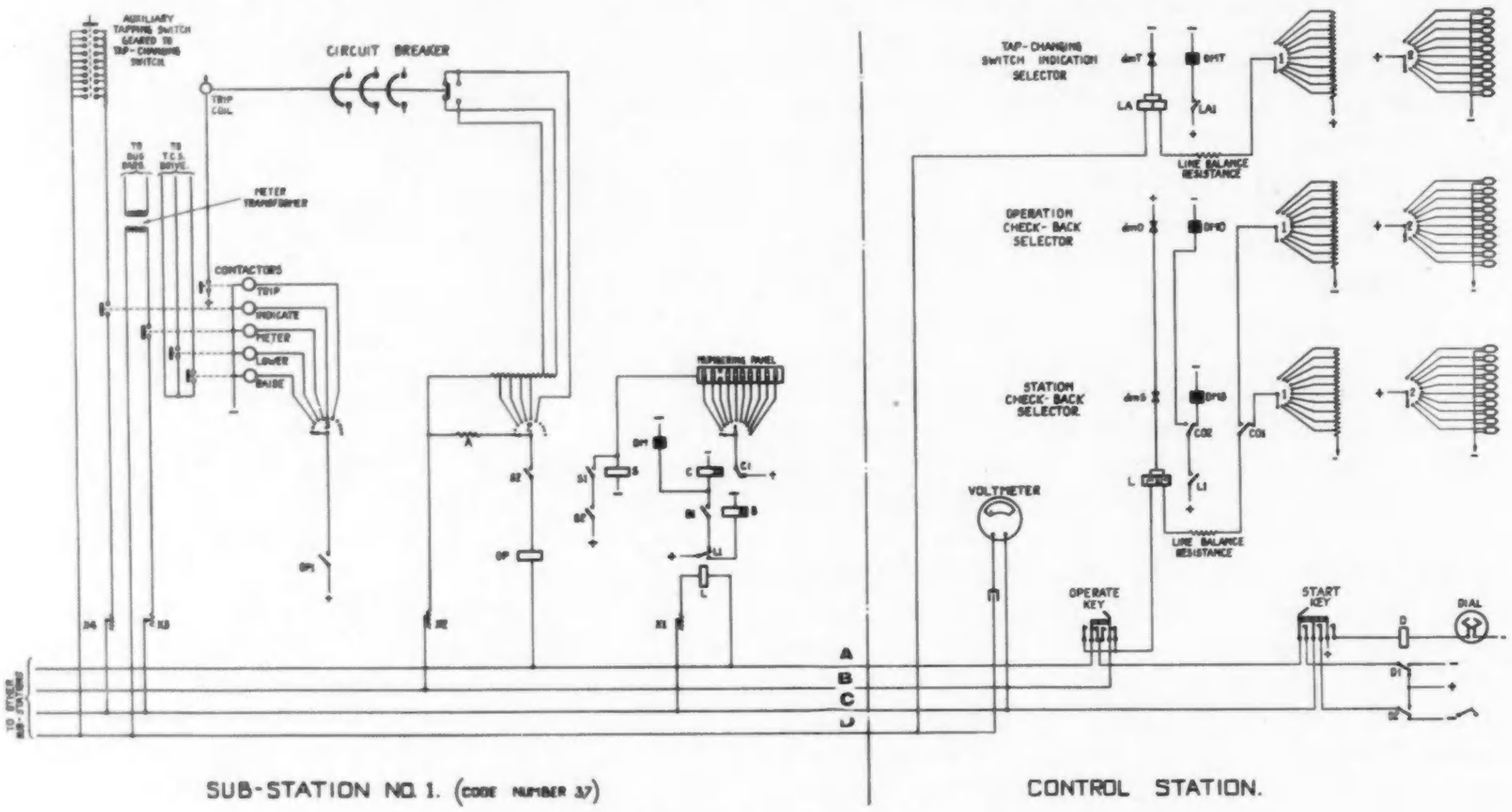

Fig. 6.—Arrangement of control station and sub-station No. 1, code number 37.

panel is permanently removed. At all other stations, where this strap still remains, an auxiliary circuit is completed to restore the selectors to normal and to render them inoperative to further impulses received. Only that station having 3 as the first digit of its distinctive number is therefore prepared to continue selection.

The digit 7 is now dialled, the impulses being received at all stations but effective only at that where the selector wipers are resting in position three. By this second train of impulses the wipers are advanced to position ten. When relay C releases at the end of impulsing the positive battery from wiper 1 is extended to operate relay S which locks via contacts S1 and operated contacts B2.

Additional contacts (not shown) on relay S now complete the circuit of the release magnet which operates and so returns the selector to normal.

To summarize the above, the selectors at all stations are at normal, but at the selected station relay S is locked in its operated position.

The following circuit can now be traced. Negative battery at the control station, operated contacts D1, operated contacts of the start key, normal contacts of the operate key, line A to the selected sub-station, polarized relay OP, operated contacts S2, wiper 2 of the selector, home bank contact, resistance A, variable resistance X2, line B to the control station, normal contacts of the operate key, one winding of relay L, interrupter springs dmS and dmO to positive battery.

The resistance A is different in value at each sub-station and, as the variable resistance X2 is set to compensate for the different lengths of line to each station, a current will flow in one winding of relay L at the control station which will be determined in value by the particular station selected. Thus, if No. 1 sub-station were selected, a current of 10 milliamperes might be flowing, while in the case of No. 2 the value might be 20 milliamperes, and so on increasing by 10 milliamperes for each station on the system. The minimum current, *i.e.*, 10 milliamps., is sufficient to operate the relay.

In the present example it will be assumed that the first sub-station has been selected by dialling number 37 and that the value of the fixed resistance A is so proportioned as to give a current of 10 milliamps. in relay L at the control station. Operated contacts L1 connect positive battery via normal contacts CO2 to operate the driving magnet

DMS of the station check-back selector. This causes the interrupter springs dmS to open and relay L is released. Contacts L1 open the circuit of DMS, allowing the selector to step to its first position, and close contacts dmS. Wiper 1 now being on the first bank contact the following circuit can be traced. Positive, normal contacts dmO and dmS, second coil of relay L, line balance resistance, normal contacts CO1, wiper 1, bank contact, resistance to negative.

The line balance resistance is equal in value to the resistance of the line to any sub-station plus the setting of the variable resistance at that station plus the resistance of relay OP. The resistances connected between the bank ccntacts of the control station selectors are such that when a selector is resting on its first position the resistance from the wiper to negative is equal to the value of the resistance A at the first sub-station. Similarly, when in the second position the resistance brought into circuit by the bank contacts is equal to A at the second station, and so on.

As station No. 1 (code number 37) has been selected a current of 10 milliamps is flowing in the first coil of relay L, and as the selector is resting on its first position 10 milliamps. will be flowing in the second coil. Since relay L is differentially wound there will be no resultant flux and the relay will not re-operate. It will be seen that this action is independent of supply voltage.

Should the code number of, say, No. 5 sub-station have been dialled, the station check-back selector on reaching the first position would cause 10 milliamps. to flow in the second coil, but there would be 50 milliamps. flowing in the first. The resultant flux being equal to that produced by 40 milliamps. in one coil, relay L would re-operate and step the selector to the second position, and so on until, on reaching the fifth position, the currents in the two coils would be equal at 50 milliamps. Relay L would then cease to operate.

When the selector thus comes to rest in the position corresponding to the number of the station dialled, positive battery is extended from wiper 2 to light the particular lamp associated with that position. In the original example this check-back lamp would be the first of the group, indicating correct selection of sub-station No. 1.

Selection of the operation to be carried out, *i.e.*, raising the tap changing switch by one step, is now made by dialling the pre-arranged number, which in this case is 2. Impulses are sent to the line as before, but as the selectors still remain locked out at all stations except that previously selected and checked back, they are effective at No. 1 station only, where the operation of relay L steps the selector to its second position. The circuit through wiper 2 and resistance A is opened and replaced by a circuit through wiper 2 and the first part of a set of resistances connected between the bank contacts. This destroys the balance between the two coils of relay L at the control station and causes it to re-operate.

At this stage a subsidiary circuit (not shown) associated with relay L at the control station operates contacts CO_1 and CO_2, thus connecting the operation check-back selector. From contacts L1 positive battery is now extended *via* operated contacts CO_2 to the driving magnet DMO of this second check-back selector. In exactly the same manner as already described the switch continues to step until a balance is obtained between the two coils of relay L. In the example given the balance is found when wiper 1 reaches the first bank contact, and the selector comes to rest. Wiper 2 completes the corresponding lamp circuit to indicate that the selector at the sub-station has been correctly positioned for the operation of raising the tap-changing switch.

Upon receipt of the check-back signal the operate key is depressed, so reversing the direction of current flowing in lines A and B and through relay OP at the sub-station. Relay OP, which is polarized in such a direction that it does not operate until the key is depressed, connects positive battery from contacts OP_1 via wiper 3 of the selector to energize the coil of the "raise" contactor which moves the tap-changing switch one step higher.

The same sequence of operations applies for lowering the tap-changing switch, except that the last digit dialled is 3.

Other numbers are allocated to the various facilities which the system offers and in each instance the two check-back signals are received before the operation is carried out. When it is desired to ascertain the voltage at the sub-station the selector is stepped to its fourth position. Upon operation the associated contactor connects the secondary of a step-down transformer, whose primary is placed across the station busbars, to the lines C and D through the line compensating resistance X3. A reading is then obtained from the meter at the control station.

The position of the tap-changing switch is indicated by means of an auxiliary tapping switch geared to it and having a set of resistances wired between the position contacts. When the indication contactor is operated a definite resistance is connected across lines C and D, depending on the position of the switch. A current of definite value consequently flows through one winding of relay LA at the control station, which functions in a similar manner to relay L to drive round the switch indication selector until a balance is found. When the selector comes to rest the position of the tap-changing switch is shown by the corresponding lamp.

The operation of reading the position of a circuit breaker and tripping it is again similar to that described, but in this case the resistances controlling the current in the line are connected directly to a contact of bank 2 at the sub-station. Either one or two resistances are in circuit, according to the position of the circuit breaker, so that one or other of two lamps associated with the operation check-back selector will indicate at the control station whether the position is "open" or "closed" respectively.

After any operation has been carried out the whole of the equipment is returned to normal by restoring the start key.

CONCLUSION.

Although the example of supervisory control described is that of a typical A.C. distribution network it is obvious that the possible applications of the system are numerous. As a relatively simple and inexpensive means of concentrating the control of equipment at one point it is suitable for use in conjunction with semi-automatic converting sub-stations, synchronous condenser equipments, mercury arc rectifier stations, induction regulator plant, hydraulic and sewage-pumping stations, hydro-electric power stations and many other types of equipment.

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